Development of a methodology of Dynamic LCA applied to the buildings

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DEDICATION

To my mother, farther, and to all my family who are always warmly watching over me from Japan.

To my friends from all over the world who have always been by my side.

To Daisaku Ikeda, my life mentor who encourages me to find the purpose and mission of life.

To humanity of which I sincerely believe in its limitless potential to solve environmental issues.

"For what purpose should one cultivate wisdom?

May you always ask yourselves this question!

Only labor and devotion to one's mission in life give life its worth."

By Daisaku Ikeda

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NOMENCLATURE

ADEME	Agence de l'Environnement et de la Maitrise de l'Energie
DHW	Domestic Hot Water
COP	Coefficient of Performance
CRF	Cumulative Radiative Forcing
CSTB	Centre Scientifique et Technique du Bâtiment
DES	Dynamic Energy Simulation
DLCA	Dynamic Life Cycle Assessment
EER	Energy Efficiency Ratio
EHPD	Environmental and Health Product Declaration
EN	Energy Network
EPD	Environmental Product Declaration
EPIC	Établissements Publics à caractère Industriel et Commercial
F&EC	Façades and exterior carpentry
F&I	Foundations and Infrastructure
FDES	Fiche de Déclaration Environnementale et Sanitaire
FU	Functional Unit
GHG	Greenhouse Gas
GMTC	Global Mean Temperature Change
GTP	Global Temperature Potential
GWP	Global Warming Potential
H&MEWS	Highways and Miscellaneous External Works
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
IRF	Impulse Response Function
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LISBP	Laboratoire d'Ingénieurie des Systèmes Biologiques et des Procédés
LIST	Luxembourg Institute of Science and Technology
LTECV	Loi de Transition Energétique pour la Croissance Verte
MDEGD	Module de donnée environnemental générique par default
MEEM	Ministère de l'Environnement, de l'Energie et de la Mer
MEIN	Ministère de l'Economie, de l'Industrie et du Numérique
MTES	Ministère de la Transition Ecologique et Solidaire
P&IC	Partitioning, lining, suspended ceiling, interior carpentry
PEP	Product Environmental Profile
PVC	Polyvinyl Chloride
RE	Reglmentation Environnemental
RTFF	Roofing, Tightness, Framework, Flashing
S&M	Superstructures and Masonry
SEER	Seasonal Energy Efficiency Ratio
SETAC	Society for Environmental Toxicology and Chemistry
SF	Sanitary Facilities
SNBC	Stratégie Nationale Bas Carbone

ABSTRACT OF THE THESIS

The building sector is a key actor to meet the reduction targets in terms of energy consumption and greenhouse gases (GHG) emissions. Life Cycle Assessment (LCA) is the most used method for assessing the environmental impacts of a system. In the building sector, the LCA method was adapted with appropriate and simplified tools in order to encourage stakeholders to evaluate the environmental performance of their building products. However, LCA method has some limitations, one of which being the lack of "time dimension" that mainly concerns three points: (i) Lack of consideration of temporal evolution of the system under LCA study, "building system" in our case, (ii) Lack of consideration of temporal discrepancy of activities and associated emissions, (iii) Lack of consideration of dynamic characteristics of environmental impacts (stationary conditions, fixed time horizon, etc.).

The long lifespan of buildings (of 50 to 100 years) implies temporal evolution of the building system and of the world around, constraining us to include this temporal evolution in the environmental assessment.

In this context, the primary objective of the thesis is to develop a dynamic LCA methodology applied to the building sector, on the basis of DyPLCA tools. The proposed methodology uses a database gathering time-variable parameters of the building system, developed in this thesis. This temporal information is used together with a specific inventory of the building sector (INIES) and with generic LCA database (ecoinvent). Temporal life cycle inventory (LCI) is then obtained with DyPLCA tool. A dynamic model for climate change is used to propose a new vision with temporal impact indicators.

The dynamic LCA methodology of buildings is then applied to a building case study in quest of responses to the following questions:

- For which kind of study and in which context does dynamic LCA become relevant to be used with respect to the conventional LCA?
- Does the action priority change between conventional and dynamic LCA results?

Dynamic LCA provides important information on the temporal profile of impacts. The same amount of GHG emissions has a lower effect on temperature peaks when emissions are spread over a long period. The distinction is made between the various GHG, especially according to their lifetime. Instantaneous and cumulated effects (indicators) should be considered in a complete analysis. Actions for mitigation and

adaptation need to be decided according to different types of construction product families. Besides, it is necessary to adapt the impact reduction efforts according to the chemical substances. The family producing methane causes a sudden increase in temperature in the short term, while the long-term persistent impact is rather due to carbon dioxide emissions.

Moreover, the beneficial or harmful effect of biogenic carbon could be managed with appropriate timing of its capture and emission. By comparing with conventional LCA, the key actions for the GHG's reduction of construction products could change with the new dynamic impact indicator of increase of the average temperature, according to the different time horizons of the analysis. Therefore, it seems necessary to choose the moment in the future for which to propose a GHG reduction strategy.

RÉSUMÉ DE LA THÈSE

Le secteur du bâtiment est un acteur clé pour aider la France à atteindre ses objectifs de réduction en matière de consommation d'énergie et d'émissions de gaz à effet de serre (GES). L'analyse du cycle de vie (ACV) est la méthode la plus utilisée pour évaluer les impacts environnementaux d'un produit ou d'un système d'une manière systématique et holistique sur l'ensemble de son cycle de vie. Dans le secteur du bâtiment, la méthode ACV a été adaptée avec des outils appropriés, simplifiés, pour inciter les acteurs du bâtiment à évaluer la performance environnementale de leur produit. Cependant, la méthode ACV présente des limites dont une est le manque de notion de « temps », qui touche notamment trois points: (i) Manque de considération de l'évolution temporelle des systèmes, du système « bâtiment » dans notre cas, (ii) Non prise en compte du décalage temporel des activités et donc des émissions, and (iii) Non prise en compte du caractère dynamique des impacts environnementaux (conditions stationnaires, ou équilibre, horizons de temps fixes, etc.)

Dans ce contexte, l'objectif de la thèse est de développer une méthodologie d'ACV dynamique appliquée au bâtiment sur la base du projet ANR DyPLCA. Dans ce projet ont été développés un modèle théorique et un outil opérationnel de calcul de l'inventaire de cycle de vie dynamique (deuxième problème) et d'évaluation des impacts dépendant du temps (troisième problème) pour le réchauffement climatique et la toxicité.

La longue durée de vie du bâtiment (ordre de 50 à 100 ans) implique l'évolution temporelle du système bâtiment (e.g., technologies liés au bâtiment, comportement des occupants). En parallèle, le monde autour change aussi (e.g., technologies, infrastructure). Il apparaît donc nécessaire de prendre en compte l'évolution temporelle du système dans son évaluation environnementale.

La méthodologie proposée utilise une base de données des paramètres variables du système bâtiment, développée dans cette thèse. Ces informations sont utilisées avec des bases de données d'ACV du domaine du bâtiment et généralistes (ecoinvent) pour construire un inventaire du cycle de vie temporalisé à l'aide des outils de calcul SimaPro et le logiciel DyPLCA. Un modèle dynamique pour le changement climatique est utilisé pour proposer une vision nouvelle avec des indicateurs d'impact temporalisés.

La méthodologie d'ACV dynamique des bâtiments est appliquée à un cas d'étude avec trois maisons individuelles accolées pour répondre à des questions suivantes :

- Pour quelles types d'études (e.g., mitigation ou adaptation ? quel secteur industriel ?), est l'ACV dynamique pertinente ?
- Est-ce que le levier d'action et la décision à prendre changent entre l'ACV conventionnelle (attributionnelle) et dynamique ?

L'ACV dynamique permet d'obtenir des informations importantes sur le profile temporel des impacts. La même quantité des émissions de GES a un impact de changement climatique plus bas lorsque les émissions sont réparties sur une période longue. Les actions pour la mitigation et l'adaptation doivent être décidées selon différents types de famille de produits de construction. Ainsi, il est nécessaire d'adapter les efforts de réduction d'impacts en fonction des substances chimiques. La famille produisant du méthane (par exemple en fin de vie) provoque une augmentation brutale de la température à court terme, tandis que l'impact persistant à long terme est plutôt dû à l'émission du dioxyde de carbone. Par ailleurs, l'effet bénéfique ou néfaste du carbone biogénique pourrait se gérer avec un calendrier approprié de son captage et émission. Ainsi, en comparant à l'ACV conventionnelle, les leviers d'actions pour la réduction des GES de produits de construction pourraient changer avec le nouvel indicateur dynamique d'augmentation de la température moyenne, selon les différents horizons temporels de l'analyse. Il est nécessaire de choisir le moment dans le futur pour lequel proposer une stratégie de réduction des GES.

RÉSUMÉ ÉTENDUE

Le secteur du bâtiment est un acteur clé pour aider la France à atteindre ses objectifs de réduction en matière de consommation d'énergie et d'émissions de gaz à effet de serre (GES). L'analyse du cycle de vie (ACV) est la méthode la plus utilisée pour évaluer les impacts environnementaux d'un produit ou d'un système d'une manière systématique et holistique sur l'ensemble de son cycle de vie. Dans le secteur du bâtiment, la méthode ACV a été adaptée avec des outils appropriés, simplifiés, pour inciter les acteurs du bâtiment à évaluer la performance environnementale de leur produit. Cependant, la méthode ACV présente des limites dont une est le manque de notion de « temps », qui touche notamment trois points : (i) Manque de considération de l'évolution temporelle des systèmes, du système « bâtiment » dans notre cas, (ii) Non prise en compte du décalage temporel des activités et donc des émissions, and (iii) Non prise en compte du caractère dynamique des impacts environnementaux (conditions stationnaires, ou équilibre, horizons de temps fixes, etc.).

Dans ce contexte, l'objectif de la thèse est de développer une méthodologie d'ACV dynamique appliquée au bâtiment permettant de prendre en compte tous ces trois aspects dynamiques. Ce développement a été réalisé sur la base du projet ANR DyPLCA (co-financeur de thèse).

La longue durée de vie du bâtiment (ordre de 50 à 100 ans) implique l'évolution temporelle du système bâtiment (e.g., technologies liés au bâtiment, comportement des occupants). En parallèle, le monde autour change aussi (e.g., technologies, infrastructure). Il apparaît donc nécessaire de prendre en compte l'évolution temporelle du système (1er problème) dans son évaluation environnementale. Le premier travail de thèse a donc constitué d'identifier les paramètres dynamiques clé et de développer une base de données des paramètres variables du système bâtiment.

Dans le projet DyPLCA, ont été proposé un modèle théorique et un outil opérationnel permettant de calculer l'inventaire de cycle de vie dynamique (2ème problème). La temporalisation des flux d'inventaire est réalisée en décomposant la matrice de l'inventaire et établissant la chaine des procédés et approvisionnements complexe qui compose un système de cycle de vie des processus en *premier plan* (processus directement liés à l'unité fonctionnelle, flux de référence) et *arrière-plan* dans le temps (outil DyPLCA : http://dyplca.pigne.org/). Afin d'appliquer leur modèle dynamique au cas de bâtiment, l'adaptation a été faite notamment pour permettre de prendre en compte le processus de système bâtiment arrivant dans un futur et à long terme (e.g., remplacement, rénovation, fin de vie, mix énergétique futur) vue la longévité du bâtiment.

Enfin, l'évaluation des impacts dépendant du temps (3ème problème) pour le réchauffement climatique (i.e., forçage radiative instantané et cumulé, et changement de la température moyenne global) et la toxicité a également été écrit sur le langage python dans le cadre du projet DyPLCA.

La méthodologie de l'ACV dynamique appliquée aux bâtiments intégrant ces trois aspects dynamique a été développée par ce travail de thèse. Elle utilise la base de données des paramètres variables du système bâtiment. Ces informations sont utilisées avec des bases de données d'ACV du domaine du bâtiment (INIES) et généralistes (ecoinvent) pour construire un inventaire du cycle de vie temporalisé à l'aide des outils de calcul SimaPro et le logiciel DyPLCA. Un modèle dynamique pour le changement climatique est utilisé pour proposer une vision nouvelle avec des indicateurs d'impact temporalisés.

Le schéma suivant illustre le cadre général de la méthodologie d'ACV dynamique appliquée aux bâtiments, développé dans ce travail de thèse. Le détail des étapes est explicitement présenté dans la section 2.3.

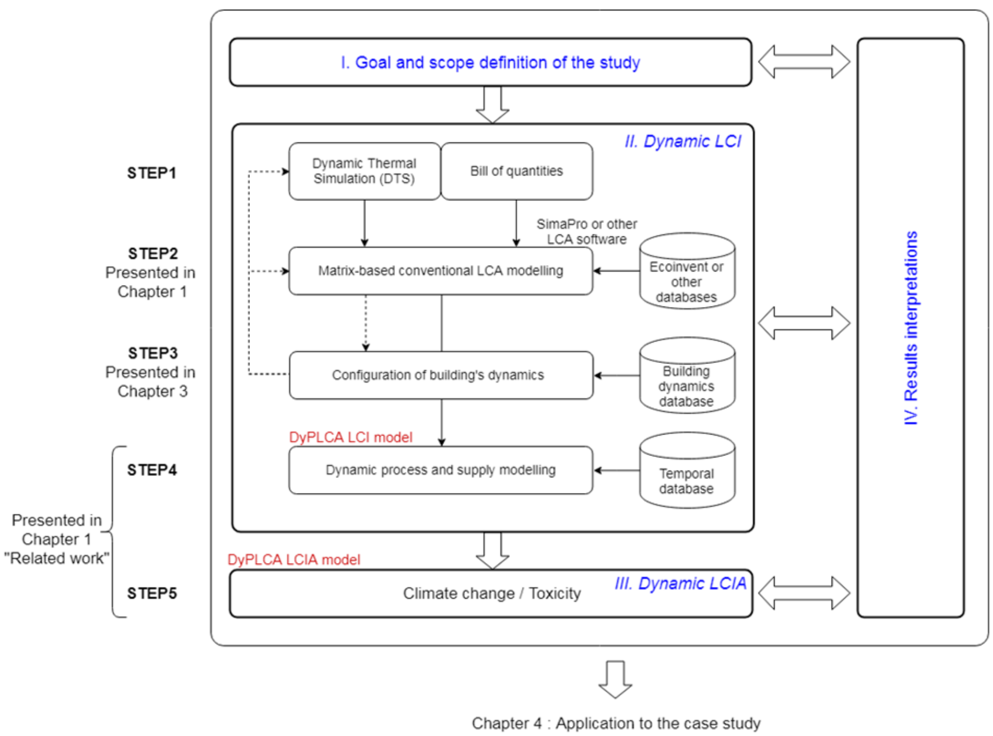


Figure I : Cadre général de la méthodologie d'ACV dynamique appliquée aux bâtiments

Cette méthodologie a été appliquée à un cas d'étude avec trois maisons individuelles accolées en bois pour répondre à des questions suivantes :

- Pour quelles types d'études (e.g., mitigation ou adaptation ? quel secteur industriel ?), est l'ACV dynamique pertinente ?
- Est-ce que le levier d'action et la décision à prendre changent entre l'ACV conventionnelle (attributionnelle) et dynamique ?

Dans cette étude de cas, indicateurs dynamiques de changement climatique ont été calculé en fonction du temps sur une période de 500 ans. Le détail des impacts de changement climatique dynamique des dix différentes familles de produit de construction, ainsi que de la variété des scénarios de consommation d'énergie a été analysé.

L'ACV dynamique permet d'obtenir des informations importantes sur le profile temporel des impacts. Les paramètres déterminants l'impact de changement climatique d'un système sont la nature et la quantité des GES émises et captés dans la frontière du système et le profil temporel des émissions. La durée de vie et le forçage radiatif sont spécifique à chaque GES et l'intensité des risques liés à la perturbation climatique dépend de la caractéristique dynamique de chaque gaz : i) des gaz ayant une durée de vie courte avec le forçage radiatif élevé (e.g., CH_4, HFC-134a) provoque une augmentation significative et brutale de température à court termes, tandis que ii) des gaz ayant une durée de vie longue, particulièrement le CO_2, ont des impacts persistants à long termes dû à leur effet cumulatif élevé. De plus, le profil temporel des émissions (ponctuel ou continu, période d'émissions), qui se diffère significativement selon la famille de produit de construction, détermine l'intensité de l'impact et si l'impact persiste sur une période longue. Par exemple, la même quantité des émissions de GES a un impact de plus bas lorsque les émissions sont réparties sur une période longue. Les actions pour la mitigation et l'adaptation doivent donc être adaptées selon différents types de famille de produits de construction et fonction des substances chimiques.

Par ailleurs, l'effet bénéfique ou néfaste du carbone biogénique pourrait se gérer avec un calendrier approprié de son captage et émission. Ainsi, en comparant à l'ACV conventionnelle, les leviers d'actions pour la réduction des GES de produits de construction pourraient changer avec le nouvel indicateur dynamique d'augmentation de la température moyenne, selon les différents horizons temporels de l'analyse. Il est également nécessaire de choisir le moment dans le futur pour lequel proposer une stratégie de réduction des GES en plaçant le système étudié dans le contexte actuel de stratégie climatique globale.

PUBLICATIONS

Scientific article published in international and peer-reviewed journal

Negishi, K., Tiruta-Barna, L., Schiopu, N., Lebert, A., Chevalier, J. (2018). An operational methodology for applying dynamic Life Cycle Assessment to buildings. Building and Environment. 144, 611–621

Negishi, K., Lebert, A., Almeida, D., Chevalier, J., Tiruta-Barna, L. (2019). Evaluating climate change pathways through a building's lifecycle based on dynamic life cycle assessment. Building and Environment. 164, 106377

Conferences with abstracts

Negishi, K., Tiruta-Barna, L., Pigné, Y., Gutiérrez, T. N., Schiopu, N., Lebert, A., Gibon, T., Schaubroeck, T., Popovici, E., Benetto, E. 2018. Methodological improvements through dynamic approaches for the life cycle assessment of buildings. SETAC Europe 28th Annual Meeting. (poster)

Negishi, K., Tiruta-Barna, L., Pigné, Y., Gutiérrez, T. N., Schiopu, N., Lebert, A., Gibon, T., Schaubroeck, T., Popovici, E., Benetto, E. 2018. Assessing Impact on Climate Change using a dynamic LCA method on French buildings. EcoBalance 2018. (oral)

Negishi, K., Tiruta-Barna, L., Pigné, Y., Gutiérrez, T. N., Schiopu, N., Lebert, A., Gibon, T., Schaubroeck, T., Popovici, E., Benetto, E. 2019. Evaluating climate change pathways through a building's lifecycle based on dynamic impact assessment metrics. SETAC Europe 29th Annual Meeting. (poster)

Work shop presentation

Negishi, K., Tiruta-Barna, L., Pigné, Y., Gutiérrez, T. N., Schiopu, N., Lebert, A., Gibon, T., Schaubroeck, T., Popovici, E., Benetto, E. 2018. An online tool for dynamic LCA – DyPLCA: application to the building sector. SETAC Europe 28th Annual Meeting. (oral)

Chapter 1

Introduction

1.1 Context of the thesis work

The Intergovernmental Panel on Climate Change (IPCC) recently published a special report discussing the impacts of global warming (IPCC, 2018). The report shows for the first time the effect of the increase of global average temperature by 1.5 °C compared to before the industrialization in the 19th century and the Greenhouse Gas (GHG) emission pathways that lead to temperature increase up to 1.5 °C. This report, approved by the governments of 195 countries and territories, is an essential scientific basis to discuss the level of confidence, the feasibility, and the effect of a 2 °C increase, after that the Paris Agreement determined to hold temperature increase up to 2°C as a long term objective (United Nations, 2015). It became clear that a 1.5 °C increase is much safer in various aspects than 2°C. Moreover, according to the report, the global warming of the planet will result in an increase of average temperature by 1.5 °C by some point between 2030 and 2052 with the underlying increase rate. It also implies that the temperature increase will attain 2°C much earlier than the end of the century.

In France, the residential and tertiary sector is the largest energy consumer accounting for 45% of French final energy consumption in 2014 (Legrand and Fink, 2014; MEEM, 2016). The residential buildings only represent two-thirds of the sector consumption. In terms of GHG emissions, it accounts for 20% of total direct emissions which are issued from product and material manufacturers. Together with the indirect emissions issued from the building's end-user energy consumption (electricity and heat), the whole sector accounts for around 25% of all French GHG emissions (MTES, 2015).

In this context, the French minister of ecological and inclusive transition signed the energy transition for green growth law (English translation for *Loi de Transition Energétique pour la Croissance Verte* – hereafter LTECV) in August 2015. This act set the framework for future environmental regulation of new buildings. According to the law, future regulation must take into account the reduction of energy and GHG emissions, considering the entire life cycle of the buildings (MTES, 2016).

LTECV and the National Low-Carbon Strategy (*Stratégie Nationale Bas Carbone* in French, hereafter SNBC) set some goals focused on the building sector concerning energy consumption and GHG emissions. First, they aim to reduce GHG emissions by 54% before 2028, which is the end year of the third carbon budget period, and at least by 86% before 2050 compared to 2013. Regarding energy consumption, the goal is to reduce by 28% compared to 2010 before 2030 (MTES, 2015).

With energy reduction measures, it will present a growing proportion of emissions from construction and product manufacturing compared to emissions from building's end-users. This fact reinforces the need to consider a whole life cycle approach for the new building's assessment. In 2050, the buildings constructed after 2013 will account for almost 40% of all existing buildings. This means that creating a mechanism to control and regulate the energy, and environmental performance of new buildings is fundamental to reduce long-term impact on French climate (MTES, 2015).

The building sector also contributes to other environmental perturbations such as the depletion of photochemical ozone, acidification, eutrophication, and air pollution through the emissions of different substances into environmental compartments. Table 1-1 shows the critical contribution of the building sector to several substance emissions such as non-methane volatile organic compound (NMVOC) representing 44% and carbon monoxide representing 40% of the total.

Table 1-1: Contribution of the building sector to the emission of main chemical substances

	SO_2	NO_X	*NMVOC*	*CO*	NH_3
Energy transformation	36%	6%	5%	1%	0%
Industrial manufacturer	49%	13%	36%	36%	2%
Residential/Tertiary	**12%**	**10%**	**44%**	**40%**	**0%**
Agriculture/Forestry	1%	10%	3%	5%	98%
Road transport	0%	56%	9%	14%	1%
Other transports	2%	6%	3%	4%	0%

Building is a complex system with multiple environmental impacts. Therefore, multidisciplinary expertise is necessary in order to improve energy and environmental performances by an approach incorporating overall embodied material and energy balances.

Life Cycle Assessment (LCA) has become an indispensable method for quantification of the environmental performance of products or services and is widely used in many sectors of activity. Environmental issues of buildings concerning both energy and embodied materials have been increasingly acknowledged in the literature, with methodological developments for environmental assessment of buildings illustrated through case studies (Peuportier, 2001; Gerilla et al., 2007; Blengini, 2009). Different types of building structures, scenarios of replacement and refurbishment phases, construction products, and energy consumption by end-users have been compared in terms of their environmental performance. Moreover, some studies focused on energy use throughout the buildings' lifetime, investigating how to estimate orders of magnitude of energy required from the construction to building demolition (Cole and Kernan, 1996; Adalberth, 1997). Indeed, construction and demolition of a building generate a considerable amount of waste, which would lead us to consider recycling of demolition waste.

In 2018, the French government launched an experimentation project "*E+C-*" in order to prepare French new energy and environmental regulations "RE2020 (2020 Environmental regulation)", which is based on life-cycle approach (FME and MTES, 2016). The European project "Levels" is also based on the concept of applying a life-cycle approach to building design (JRC European Commission, 2017, 2018).

The LCA is under the management of ISO 14000, the series of international standards addressing the sustainable study. According to the ISO 14040 standard, LCA is a "compilation and evaluation of the inputs, outputs from the potential environmental impacts of a product system throughout its life cycle." A complete LCA must follow the four steps as shown in Figure 1-1.

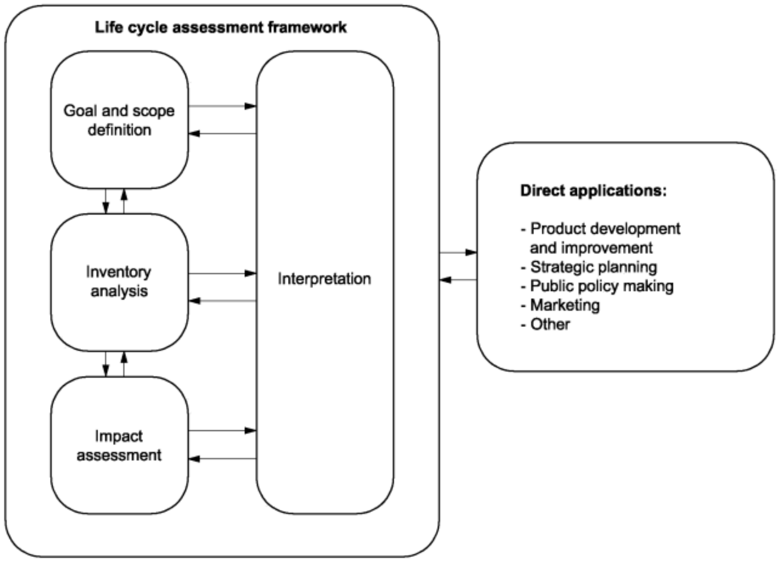


Figure 1-1: Life Cycle Assessment framework (ISO, 2006a, 2006b)

The brief description of LCA steps is given here for those who are not familiar with the LCA.

First, the *goal and scope* of the study must be defined. Following aspects are formalized: the reason for study, the public interest, product system boundaries, functional unit, allocation methods, and impact categories, among others.

Second, *Life Cycle Inventory (LCI) analysis* collects data and defines calculation procedures to quantify relevant inputs and outputs of a product system.

Third, the *Life Cycle Impact Assessment (LCIA)* evaluates the potential environmental impacts by associating LCI with specific environmental impact categories and category indicators. There is a set of methods to transform LCI to the impact categories, and the choice of the method depends on the assessed impacts and the purpose of the study.

Finally, *Interpretation* is a transversal phase of LCA. It allows the results to be delivered consistently with the defined goal and scope. The result interpretation also permits to reach conclusions, explain limitations and provide recommendations. This phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal.

Many environmental standards currently exist in the construction sector, at national levels as well as in Europe. For example, the European standard EN 15978 on the assessment of the environmental performance of buildings applies to new and existing buildings and refurbishment projects (CEN, 2012a). These standards give the rules for quantitatively evaluating the environmental performance of buildings based on the lifecycle approach, i.e., accounting for impacts at each stage of the building lifecycle. Different lifecycle-based tools complying with these rules or environmental regulations have been developed to help to design sustainable buildings with respect to country-specific contexts, e.g., ELODIE in France. We evaluate the environmental performance of a building by multiple impact categories. The French norm of building LCA defines 26 impact categories.

Many recent studies attempted the extension of the LCA application to enlarge scopes and objectives, such as regionalized or localized LCA, consequential LCA, social LCA, LCA towards ecosystem services, etc. One of these emerging LCA methods is dynamic LCA, with respect to "time dimension."

Despite all the efforts being made on the development of LCA tools along with attempts to regularly upload environmental data, there are no tools (methods, norms, or databases) enabling temporal characteristics to be taken into account, which are explicit and specific to buildings.

In this context, the need for a more realistic evaluation of the environmental performances over extended time frames leads us to consider a dynamic LCA approach adapted and completed for application to the building sector.

1.2 Problem statement

The primary goal of this thesis is to provide complete dynamics of LCA methodology for buildings that overcome three methodological limitations of the conventional LCA:

- Lack of consideration of temporal evolution of the system under LCA study, a "building system" in our case
- Lack of consideration of temporal discrepancy in activities and associated emissions
- Lack of consideration of dynamic characteristics of environmental impacts (stationary conditions, fixed time horizon for impact analysis, etc.)

Given our particular attention on the “time” dimension, we set the followings three dynamic aspects as central for the thesis:

- Understanding and integrating the temporal evolution of a building system into building LCA,
- Integration of process and supply dynamics of technological and environmental flows,
- Calculation of environmental impacts depending on time.

1.2.1 Temporal evolution of a building system

While building-LCA studies have demonstrated methodological improvements integrating more and more complex elements of the building system, its evolution over the life cycle has remained beyond the scope of studies as buildings have particularly long lifetimes compared to other products or services. Building systems are composed of elements that evolve in time and are characterized by time-dependent parameters. At the technological level related to the building sector, the degradation of technical performances of buildings may be one of the key dynamic parameters. On the other hand, energy consumption varies with time, and its variation is determined by technological parameters, occupants’ behaviour, characteristics of energy equipment, and climate conditions. Another aspect that influences energy consumption by a building system is the economic and environmental context. The evolution of policy rules, e.g., national energy strategies and environmental regulations, may encourage the construction sector to reduce material and energy use and can stimulate a reduction of related environmental impacts

Therefore, decisions for construction materials, maintenance, replacements, and refurbishment, together with scenarios of the end of life, should be placed in the context of national and European regulations that could change over time depending on the energy, environmental and economic background. The electricity production mix and, more generally, the energy production resources vary over time depending on the availability of energy resources, the economic situation of a country, climate and agriculture for renewable energy development, etc. Some of these dynamic parameters considerably impact LCA results for buildings. Figure 1-2 shows possible dynamic aspects in a “*building system*.”

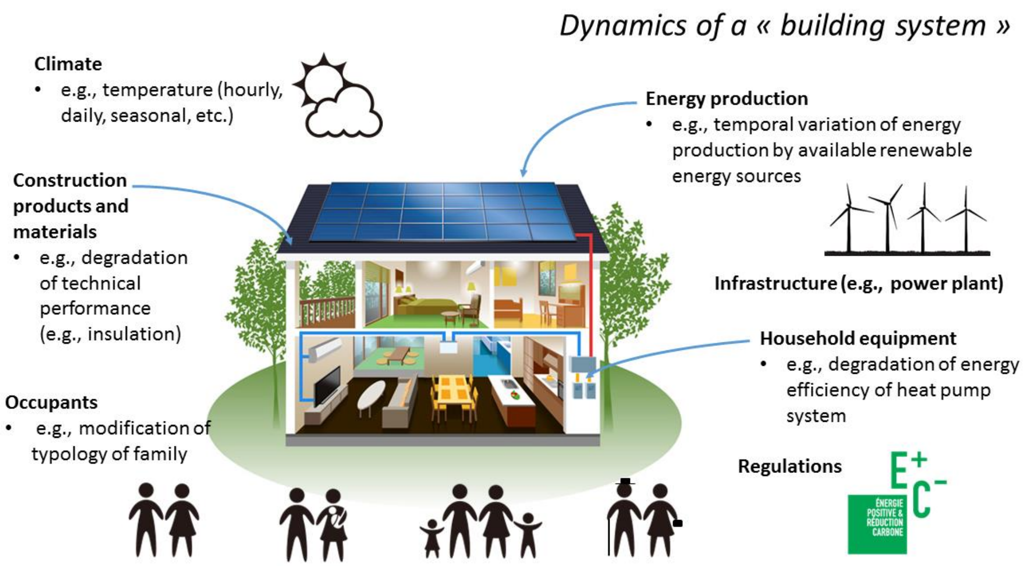


Figure 1-2: Dynamic aspects within a building system

1.2.2 Process and supply dynamics through technological and environmental flows

As stated in earlier sections, buildings have a very long lifetime compared to other products or systems. In consequent, the temporal discrepancy of activities and associated emissions are ranging from several years (e.g., related to regular maintenance of building equipment, wall paintings) to several decades (e.g., between the construction and end-of-life activities) following the *foreground* system of a building LCA. The production and supply chain in the *background* system, in reality, is also scheduled in fine over time because processes are related to each other (e.g., a wooden door production depends on the processing of door frame production, which is related to the supply of wooden material to a factory, and so on…)[1].

Moreover, the technological and environmental flows between processes are dynamically changing in time. For example, the supply of wood chips as a by-product from wood thinning is not constant but rather time-variable and periodical, therefore associated environmental burdens are also time-variable and periodical. Otherwise, the traditional LCA method considers that these flows happen in a simultaneous and

[1] See the section 3.2.1 for the definition of *foreground* and *background* system

instantaneous way without any temporal consideration. Inventory information is considered to be kept over a certain period for emissions analysis.

The goal of this dynamic aspects is to temporally disaggregate LCI in the background as well as the foreground. DyPLCA ANR project has preliminarily studied this limit and proposed tools (method, database, and calculation software) for temporal LCI calculation (see Annex I).

Figure 1-3 illustrates how a system under study is dynamic and that a system is scheduled strictly following the "cradle to grave" concept.

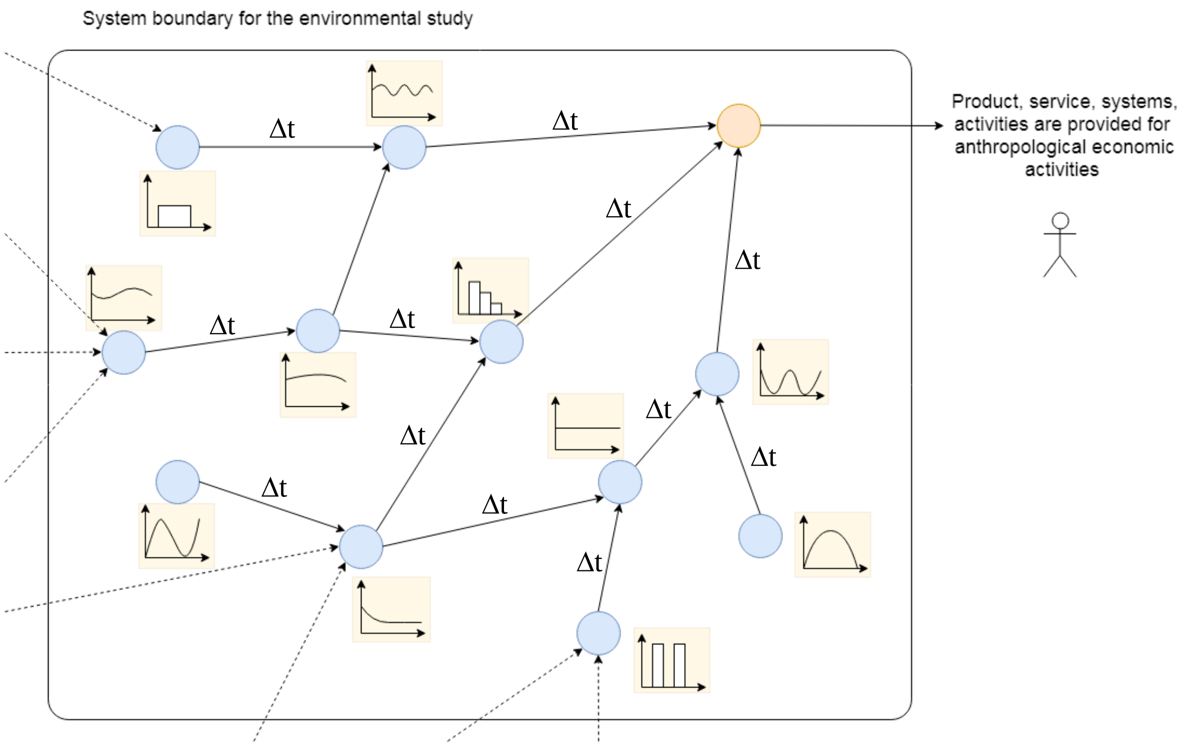


Figure 1-3: Dynamics (technological and environmental flows in function of time) through a whole system network to provide a functional unit (orange node)

1.2.3 Time-dependent impacts

Conventional metrics for the calculation of environmental impacts uses the characterization factors (CF) that allow evaluation of a product and system with only a single score of impacts. Thus, it is easy to compare the environmental performances between different systems. However, the traditional CFs are generally considered as proportionality constants and are calculated with very simplified hypotheses. The temporal decay of the environmental compartment response to each substance is not or only partially considered. Besides, the impacts are analyzed within a fixed (e.g., global warming potential) or infinite horizon time (e.g., toxicity), and most of them are analyzed in steady state conditions. In reality, the environmental burdens due to chemical substances emitted into different environmental compartments (air, water, soil) are dynamically changing over time. The environmental mechanisms are complex, and the environmental impact evaluation only in a single score drastically reduces the information and could mislead our decisions with respect to the environmental issues.

Therefore, the goal for this problem will be achieved by using characterization functions instead of characterization factors as stated in Cherubini et al. (2011).

At the moment, there are still few dynamic methods of impact calculations such as for climate change and toxicity. Therefore, the work of this thesis focuses on the impact category so-called “dynamic climate change impacts” through a case study.

For the climate change impacts, the traditional characterization factor called Global Warming Potential (GWP) accounts for the radiative forcing of atmospheric substances. The model follows the method proposed by the Intergovernmental Panel on Climate Change (IPCC, 2013). In this model, the global warming effect of specific substances in the atmosphere on a fixed time horizon (e.g., 20, 50, 100 years), i.e., cumulated radiative forcing until this horizon, is normalized by that of carbon dioxide (i.e., impact equivalent to CO_2). As a result, the impact can be evaluated as a single score (kg CO_2 eq., at midpoint). However, the information concerning the dynamic behavior is lost. Figure 1-4 shows the radiative forcing evolution of the three main GHGs: CO_2, CH_4, and N_2O.

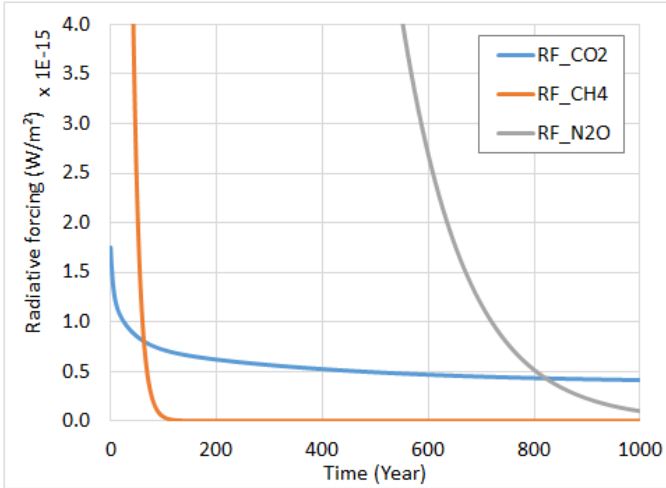


Figure 1-4: Radiative forcing evolution over 1000 years in response to the emissions of 1kg of CO_2, CH_4, and N_2O at time 0 (IPCC, 2013)

The graph shows two characteristics: the impact amplitude and the impact persistence, which are the lacking information in the GWP metric. We can simply observe that the first years the impact (radiative forcing until around 100 years) of CH_4 is higher than that of CO_2. However, the effect of CO_2 persists much longer than that of CH_4. This fact teaches us that the result interpretation of climate change is not as easy as using a single score analysis, and this complexity becomes even more considerable when combining temporally disaggregated emissions and time-dependent impact models.

1.3 Research questions and thesis outline

Dynamic LCA is still at the beginning of its development, and most of the studies handle "time dimension" only in one of three problems stated in Section 1.2. The present work intends to go beyond the state-of-art of the building LCA. At the same time, a dynamic approach will require more steps to proceed to dynamic LCI and LCIA modelling, and the obtained results will be more complex and difficult to be interpreted. Thus, dynamic LCA could introduce complexity, while the stakeholders ask for (very) simplified tools. For these reasons, it is important to keenly seek out responses to the following research questions:

- Can a complete dynamic LCA approach applied to the building be feasible
- For which kind of study and in which study context, does dynamic LCA become more relevant to be used comparing to conventional LCA?

- Does the action priority of GHG reduction change between conventional and dynamic LCA results?

Given the above questions, the objectives of this thesis are:

- To propose a methodology of dynamic LCA applied to the buildings,
- To identify the benefit of the dynamic approach with respect to the building system.

Chapter 1 (this chapter) provides a general introduction of the environmental assessment in the building sector. We also define the problems and research objectives of the development of a dynamic LCA methodology applied to the building sector.

Chapter 2 presents the state-of-art in the field of dynamic LCA applied to building systems and describes the potential time-varying parameters. Then, we propose the new methodology of dynamic LCA applied to buildings.

Chapter 3 is dedicated to the development of a database collecting dynamic parameters related to the evolution within a building system.

In Chapter 4, the feasibility of the dynamic LCA study for buildings proposed in Chapter 2 is testified through a case study. An existing building is used for the case study. Some prospective scenarios of a building system are modeled with the support of collected data in Chapter 3.

Chapter 5 discusses different orientations for further work dealing with dynamic LCA development and its use. This chapter finally aims to give some responses to our research questions.

Lastly, Chapter 6 concludes the thesis work and proposes some perspectives.

The present thesis work is co-financed by the ANR Dynamic Process LCA (DyPLCA, 2014-2018) project. The main objective of the project is to develop an operational tool for performing dynamic LCA in a proper and reproducible way. The concept of the dynamic approach regards an integral solution both for dynamic LCI calculation and for dynamic LCIA calculation. The integration of scenarios of inventory data, i.e., the evolution of technological and environmental flows over time, is not in the scope of the project. The project succeeded at a modelling platform composed of software and database, with a web interface for application (http://dyplca.pigne.org/).

This new approach can be a useful tool offering the possibility of consideration from a short- to long-term system evolution. In the short timeframe of the LCA project, three different sectors were selected for the application of the dynamic LCA method: vehicle, biochemical processes, and building – in this thesis. The time dimension can be present in each of these three sectors in different ways, for example, one should consider a particular dynamics related to a chemical process, whereas others look more at the future of a system with a decennial or centennial horizon to implement political strategies.

Chapter 2

Development of modeling and simulation platform of a dynamic LCA methodology applied to buildings

2.1 Introduction

Chapter 1 introduced the general environmental issue of the building sector and the theoretical concept of the commonly used environmental assessment method in the sector, which is the Life Cycle Assessment (LCA). As early mentioned in the problem statement, the longevity is the important perspective to design a sustainable building. Therefore, the adaptation of the generic dynamic LCA to the building sector will be put in line with this perspective. The first work to be done is to understand which aspects/parameters are likely to vary not only in the short term but also in an average or long terms within a whole building system. Besides, we will identify significant aspects/parameters to be considered because a “building system” is highly complex with an incalculable number of dynamic parameters into between “cradle to grave” boundaries.

While the theoretical development of a dynamic LCA has been seen in very recent studies, the actors involved in the building sector have had recognized earlier the importance to take into account the dynamic behavior of a building system into the environmental evaluation (Scheuer et al., 2003). Meanwhile, the French building sector has already established a complete and well consensual methodology and tools (software and database) for the conventional LCA, for example, ELODIE software with French EPD system (Chevalier et al., 2010). Therefore, the improvement of the LCA method and regulations aligning with these relevant environmental assessment methods is essential so that the users can continue to be familiar with LCA tools for French buildings in the French context.

The objective of this chapter is thus to propose a methodology for considering time in LCA of buildings, and if possible, compatible with the existing databases and calculation tools.

This chapter is structured in 2 sections: Section 2.2 analyzes the state-of-art related to the dynamic LCA in the field of buildings. Section 2.3 addresses the general goal of this chapter proposing a complete framework for dynamic LCA applied to buildings. This section explains, on the basis of the elements presented in the previous sections, how to proceed to a dynamic LCA for buildings, step by step, combining different tools, models, and databases. Besides, the expected results and the main limitations of the proposed framework are presented.

2.2 Literature review

2.2.1 Time-dependent factors and parameters of a building system

Before analyzing the temporal aspects in LCA applied to buildings, this section will present various aspects of a building system expected to vary in time. In order to facilitate our understanding of how a building and its surroundings are changing, a short story of the evolution of a family is presented below (Figure 2-1).

Evolution of NEGISHI family's housing and its surroundings

In 1985, NEGISHI family purchased a new single house in Tokyo, which is based on the wood structure. In several years, the family becomes from 2 to 5 persons including 3 children. As children grow very fast, they extend the house adding two more bedrooms and another salon for more comfort in 2000. Their consumption of energy and water increases in parallel. 10 years later, all children leave the house for the reason of their work, study, marriage, etc. In 2015, they notice that there are significant material degradations and product and equipment dysfunctions after 30 years of the building occupation. Insulation materials decay, door opening and closing do not work well, windows become to be drafty, wall paint peels off, etc. At the same time, they needed to repair and replace some construction products and materials. Also, for now, that only the parent lives, the house comes to be a little bit too large. Therefore, they decide to renovate the entire house and to relive with one of the children. The renovated house has now three stories and is designed as a low energy house. The house is equipped with the new technologies of better insulation systems and a high-performance heating system with mechanical ventilation.

During this changing house and inhabitants, the surroundings are also changing. The electricity production mix has shifted from fossil fuel sources to nuclear with a marginal part of intermittent renewable energy. In the future, the mix will still be modified.

Moreover, their lifestyle, building technology, transport system, energy regulation, climate condition, and many other aspects are still changing and will continue to change in the future…

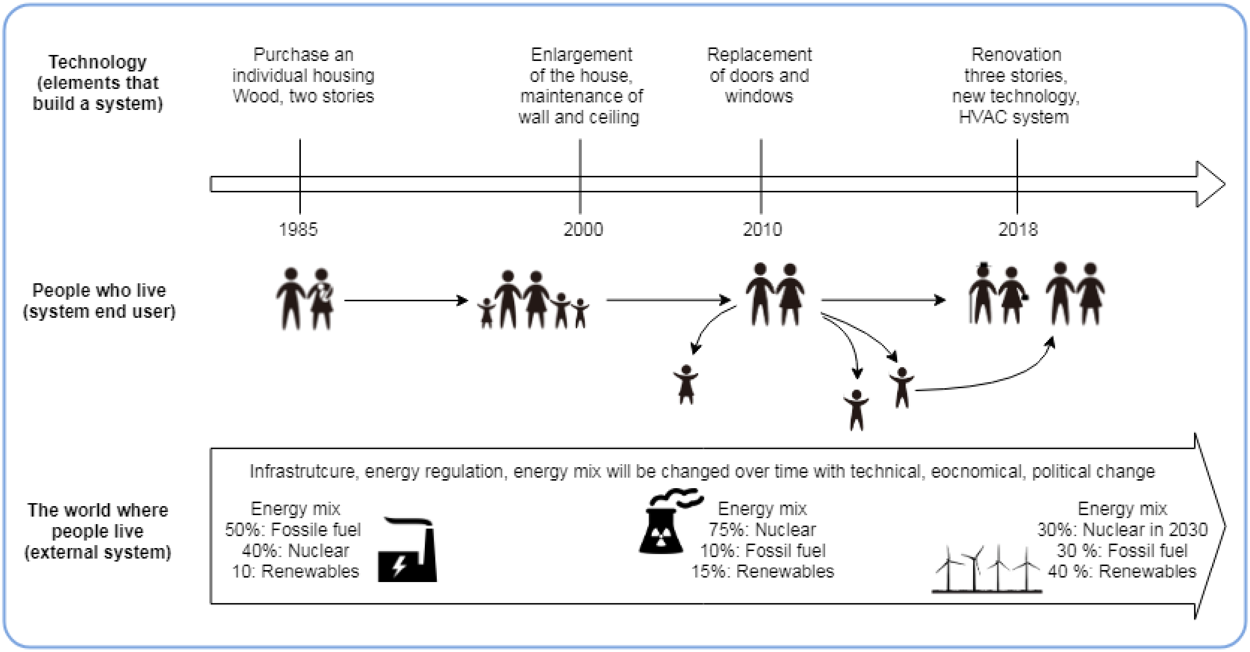


Figure 2-1: Short history of the evolution of NEGISHI family's housing over time

As this simple example shows, the technology that builds a system, people who live (system end user), and the world where people live are filled with a large number of changing factors from an instant to instant both at a short and long time scale. Hereafter, these dynamic parameters of a building system are examined on the basis of the literature review. However, this work represents a first level of LCI analysis and does not yet cover the sensitivity of LCA results related to these parameters and the uncertainty in LCA.

Technical performances related to construction products and energy equipment degrade over the long lifetime of buildings. Insulation materials deteriorate over time due to climate conditions (e.g., humidity), and the occupant needs to replace such building materials in order to maintain thermal comfort. Studies exist on how the degradation of building components (especially insulation materials) occurs over time, affecting the energy consumption (Toman et al., 2009; Stazi et al. 2014; Choi et al., 2018). One of these research works examined the durability of insulation materials in terms of their thermal-hygrometric and mechanical performances, showing a 12% increase in thermal conductivity over 25 years. The effects of such degradations on the energy performance of buildings were observed and simulated over time for different envelope structures, e.g. exterior walls, floors, and roof. It was observed that bio-based insulation materials, such as wood wool are particularly sensitive to climate conditions, and their thermal performance can deteriorate due to the variation of water content in the products (Marceau et al., 2016). Degradations of technical performance will lead to changes in energy consumption. Besides, the interaction with external factors like gases from the atmosphere may lead to some carbon dioxide absorption in the case of lime-containing materials (concrete, hempcrete, …) (Pommer and Pade, 2005; Collins, 2010).

The real durability of construction products can be significantly different from the theoretical and declared one (Talon, 2006). ISO 15686-8 defines a methodology and factors in determining the service lifespan of construction products and building equipment. According to the literature review, many building-LCA studies refer to 50 to 100 years as a lifetime of buildings. The service life of 30 years is typically used for principal components of a building (e.g., floors, façades, and roof) (JRC European Commission, 2018) and products should be replaced or refurbished at their end of life using new technologies that have emerged.

Although the technical performances of building components may diminish during the building's long lifetime, this very longevity of the building implies that it will be able to benefit from technological innovations occurring after its original construction. The relevance of taking this prospective aspect into account in LCA for long time scale studies has been discussed by Frischknecht et al. (Frischknecht et al., 2009). Prospective factors should be considered for different scales and depending on the scope of the study. Replacement, refurbishment and also the treatment of construction waste products occurring several decades after the first construction may use new technologies that are more efficient in terms of energy consumption or environmental emissions. Thus, industrial and technological improvements should lead to long time scale scenarios with high environmental quality of the buildings.

Energy consumption varies from hour to hour, day to day, week to week, season to season, and year to year, depending on various factors. The typology of inhabitants and their behaviour are variable depending on the economy, culture, or other social aspects, and play an important role in determining the energy consumption level and its temporal behaviour. From a literature review, de Meester et al. (2013) selected the three parameters having the most influence on the heating loads in a single-family house: 1) type of occupancy (e.g., family size, age), 2) management of thermal comfort (e.g. temperature set point, functioning time of energy systems) and 3) area heated (de Meester et al., 2013). They created seven levels of thermal performance for the house (from zero insulation to standard level insulation for a passive house). Each scenario uses different insulation materials in the wall, floors, and roof. If the insulation level is low, the heat load management (temperature specification and heating time) becomes important to reduce energy consumption.

On the other hand, when the house is well insulated, the type of occupancy significantly impacts the energy consumption level. Four scenarios of occupancy over 100 years, combining the above three parameters, were evaluated in terms of heating loads, and the maximal difference between scenarios reached 26%. As evoked in their discussion, in a long time scale analysis, the house should be adapted to the evolution of the family, including possible improvements in thermal insulation.

Reducing energy consumption during the building component production and during its service lifetime is a continuing goal. Lowering the environmental load of the energy used is another improvement criterion. Heat production can use thermal resources like fossil fuels, biomass, and thermo-solar systems. A large panel of electricity production technologies exist, based on fossil or renewable resources. French electricity production depends strongly on nuclear power and is characterized by a low carbon footprint, with an annual average of 105 g CO_2-eq/kWh, compared to the power production technologies of other European countries, which are mostly based on fossil fuels. For example, the average carbon intensity of electricity consumed in Europe was 447 g CO_2-eq/kWh in 2013 (Moro and Lonza, 2017).

To meet the target concerning the reduction of GHG emissions, the European Commission has proposed a framework for energy pathways towards 2050. Following this strategy, 75% of the European electricity consumption would be covered by renewable sources, with a shift in the electricity production mix and improvements in energy system efficiency (European Commission, 2012). Decarbonization is also encouraged for heating and cooling systems to ensure that the goal of limiting climate change is achieved (Lund et al., 2012). According to this study, increasing the share of district heating with respect to the total energy demand, and also accounting for the development of other heating systems (waste incineration, geothermal, solar thermal and industrial excess heat), would reduce carbon emissions at European level by 17 to 30% by 2050 with respect to the same heat demand level as in 2010. Also included in the scenario are other temporal changes in heat production systems: decreasing nuclear production, renewing power plants and existing combined fossil-fueled heat and power (CHP) plants, and developing renewable heat production. In France, the national energy strategy aims to increase the proportion of renewable energy resources to 40% by about 2030 and to reduce the nuclear production fraction from 75% to 50% by 2025 (MTES, 2018). In terms of French district heating systems, the objective for 2030 is to cover 32% of district heat consumption by renewable energy resources. The quantity of renewable heat and cooling delivered in 2012 will be multiplied by five in 2030, which will represent 3.2 Mtoe (equal to 41.9 TWh).

Another important aspect is involved in the exchange of CO_2 between different environmental compartments. For the building constructed based on wood, it is important to account for exchanges of CO_2 between the atmosphere and tree for the photosynthesis of tree. These stored CO_2 into wooden products can also be restituted into the atmosphere due to the incineration of wood at the end of life. The influence of taking into account the temporal profile of atmospheric CO_2 is previously examined in several works (Fouquet et al., 2015). There also is a process of the CO_2 uptake into the cement products, called carbonation. The amount of carbonation depends on the class of cement, inclusion rate of clinker in the cement, and the composition of the clinker (Pommer and Pade, 2005; Collins, 2010).

Table 2-1 synthesizes the state of the art studies in the field of buildings, which consider a temporal evolution of various factors susceptible to affect the environmental performances of a building system.

Table 2-1: Synopsis of the Dynamic elements of the "building system" from the state of the art

	Authors	Time-varying parameters	Time horizon to account for time-varying parameters
Construction product and materials	(Toman et al., 2009; Stazi et al., 2014; Choi et al., 2018; Marceau et al., 2016; Fouquet et al., 2015)	Technical performances (thermal, acoustic, mechanical resistances of materials); Service lifetime of construction products and materials; Material quantities (e.g., for replacements)	Year to decade ~
HVAC (Heating, Ventilation, and Air-Conditioning) system	(Beloin- Saint- Pierre et al., 2016; Frijia et al., 2012)	Energy efficiency of HVAC Generation and distribution system, Energy consumption; Service lifetime	Hour, day, month, season, to several decades
On-site electricity production (e.g., on-roof photovoltaic)	(Fouquet, 2015; Roux et al., 2016b)	Electricity production by photovoltaic system	Hour, day, month, season to several decades
Occupant behaviour	(de Meester et al., 2013)	Thermal management; Typology of family;	Year to decade ~

		Insulation material choices	
Energy production (electricity and district heating and cooling)	(Collinge et al., 2013; Fouquet, 2015; Roux et al., 2016a)	Mix of energy production resources (Composition of each fuel type in a kWh of production)	Hour, day, month, season to several decades
Carbon sequestration in wood and biogenic carbon emission	(Fouquet et al., 2015)	Quantity of carbon dioxide absorbed by and emitted from wood	Several decades to century
Carbon sequestration in other materials	(Collins, 2010; Pommer and Pade, 2005)	Quantity of carbon dioxide absorbed by, e.g. lime-containing products	Years, several decades
Retrofitting scenario	(Stazi et al., 2009)	Maintenance and renovation choices	Decade ~
Demolition scenario	(Fouquet et al., 2015)	Energy recovery and recycling technologies	Decade ~

2.2.2 Time-related aspects in conventional LCA

LCA is the common method for evaluating products, services, and activities in terms of their potential environmental impacts throughout their life cycle, supported by ISO 14040 – 14044 standards (ISO, 2006a, 2006b). According to the standards, the LCA methodology is divided into four steps. i) Goal and scope definition. ii) Life cycle inventory compilation calculating material and energy balances at the level of the processes and of the environmental interventions (substances emitted into the environment and natural resources consumed), throughout the system's lifespan. While the LCI of background processes is generic and can be obtained from databases, the foreground process inventory is case-specific and must be obtained by data collection or specific modelling for the process/product under study. iii) Life cycle impact assessment based on methods for evaluating environmental impacts. iv) Interpretation of LCA results, as a step for uncertainty and sensitivity analysis of outcomes, and recommendations for decision makers. This phase includes the analysis of a consequence of time dimension included mainly in the first three steps of the methodology.

The analysis time span is the period used for each system studied, chosen in coherence with the lifetime of this system. It is specified in the first step of LCA, i.e., the definition of the goal and scope, and represents the period for which the inventory flows are considered to be present and the LCA results are considered valid (e.g., 50 years, the lifespan of a building). In the same manner, the time boundaries of a study situate the period of interest in time (e.g., a past or a future new system).

The conventional LCA approach considers stationary conditions, static LCI being a list of environmental emissions without their occurrence time or spatial location. Environmental interventions, occurring in reality at different moments on the timescale and over different periods, are all considered equivalent with respect to the period of analysis. In the context of rapid changes of the system properties, it is important to indicate the temporality of data used, as they reflect specific conditions of the system under evaluation at a chosen moment. However, the practice of LCA is often limited by a lack of consistent and relevant data, especially for studies including prospective analysis.

Instead of being based on instantaneous and simultaneous inventory flows as in current LCA practice, the assessment can include a time dimension, integrated as temporally segmented inventories over the whole system life cycle. A time differentiated inventory, defined over distinct periods, takes account of the prospective evolution of systems over time. For the environmental evaluation of buildings having long lifetimes, time-dependent analysis with changes at different levels of systems, e.g. technologies, economy, occupant behaviours, and political rules, can be implemented within conventional LCA by defining distinct scenarios over each time period of interest.

Various LCIA methods exist for calculating environmental impacts. The basic principle of all conventional methods is to provide a characterization factor (CF) for a given combination of substance/environmental compartment/effect (or impact). Then the substance amount (i.e., LCI) is multiplied by its CF to obtain the impact result. This is the basic principle of LCA. In such approach, assumptions and simplifications have been operated at the level of CF calculation, notably by considering the environmental mechanisms in steady state (static) conditions, or considering a fixed time horizon when an integral over time is required to calculate CF for some impact indicators (e.g., GWP – global warming potential). Conventional characterization factors are thus dependent on arbitrarily fixed time horizons (e.g., 20, 50, 100 years), which constitutes a substantial limitation of the current LCIA methods. It is entirely legitimate to raise questions like, “Does today’s 1 kg of CO_2 emission have the same environmental impact as 1 kg emitted after 50 years?” Or, “Between 10 kg of CO_2 emission in a year and 1 kg of CO_2 emissions per year during ten years, which case has the most impact at a precise date?” It is not possible to answer such questions within conventional LCA, and a new approach with fully dynamic modelling of environmental mechanisms is needed.

The relevance of taking account of the temporal dimension in the LCA, at both LCI and LCIA levels, has already been discussed in past studies (Beloin-Saint-Pierre et al., 2013; Collet et al., 2014; Pinsonnault et al., 2014). Based on the previous LCA developments, we identify five aspects in LCA where time dimension intervenes.

Time horizon of data and assessments

According to the conventional LCA approach, the studies following EN15978 standard (CEN, 2012a) are carried out for a chosen reference study period. This time horizon is defined as a period covering from the impact of first environmental burdens to the latest ones through the life cycle of a system studied. LCI data is collected within a “cradle to grave” boundary, and it usually means the building’s lifetime. Then, the impact of each emission is assessed by using characterization factors for a fixed analytical horizon time. However, the conventional approach does not consider temporal disaggregation of emissions, whereas the cumulated impact from emissions at time 0 and those in the future should not be the same. Figure 2-2 illustrates the definition of the time horizon of data and assessments used in the conventional LCA.

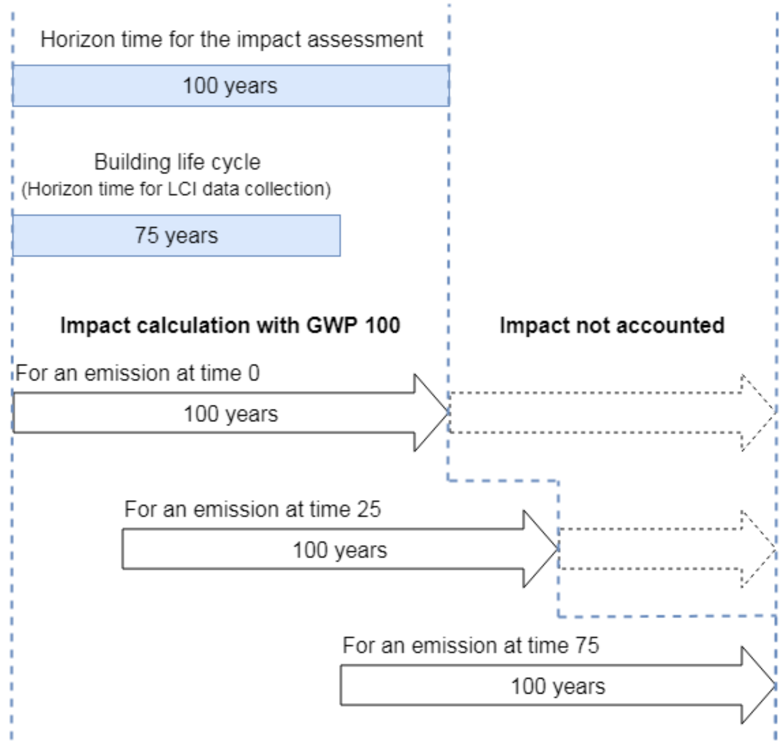


Figure 2-2: Definition of time horizon of data and assessments for the conventional global warming calculation (adjusted from Levasseur et al., 2010)

Temporal representativeness of data

The technology for our activities for material and product manufacturers, construction, renovation and demolition have changed, and alternative solutions continue to appear. For example, during the long lifetime of a building system, today's manufacturing processes for window fabrications will likely be different at its replacement phase in the future. Besides, the infrastructure in the background system (road, power plant, agriculture, etc.) has its service life and is renewed every several decades. This technological change implies the change in associated environmental impacts. Therefore, it is important to pay attention to the quality of LCI data by regularly updating them in order to increase the reliability and decrease the uncertainty of the LCA results.

However, the completeness of data is not always secured. In consequent, most conventional LCA studies consider that the technology remains the same during the life cycle of their systems. Therefore, it is important to note temporal representativeness of data used because data might be referred to specific conditions of the case study only at a given time. To overcome this obstacle related to data quality, the sensitivity analysis helps to know the variability of results and to avoid as much as possible uncertainty.

Time scale and temporal profile of data

A conventional LCI is established considering as instantaneous and simultaneous material and energy balances, and associated environmental interventions. Aggregated emissions over the lifecycle of the studied system are used as input of LCIA calculation. In consequence, chemical burdens into environmental compartments are considered in a stationary condition, and there is no dynamics. Meanwhile, dynamic LCA metrics require a range of inventory flows over time. The time scale of emissions determines the temporal profile of environmental impacts, and short- and long-term scale emissions result in different temporal behaviors according to substances. Thus, missing information on a time scale leads us to a misunderstanding of environmental impacts. Figure 2-3 illustrates two types (step and continuous) of temporal profile of CO_2 emissions in the left and their implications of global mean temperature change in the right.

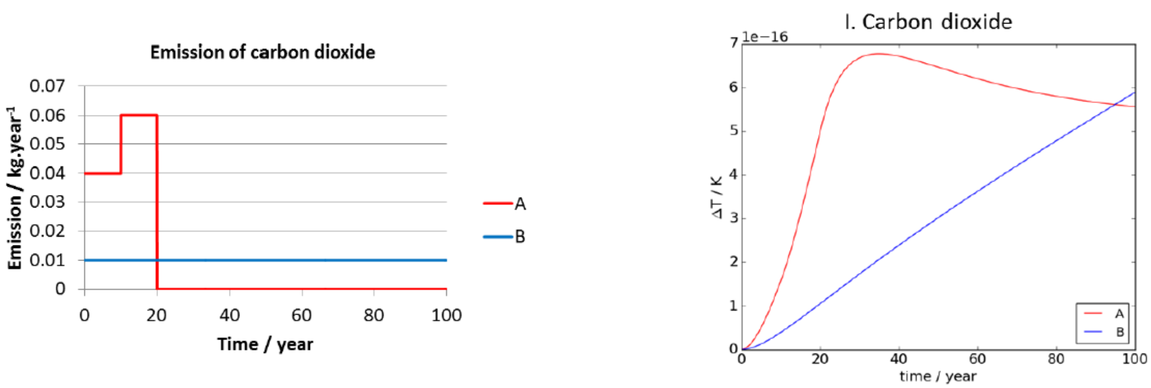


Figure 2-3: Example of different emission profiles(A: step emissions and B: continuous emissions) (left) and their impact with the indicator of global mean temperature change by (Shimako, 2017)

Time step of data

As early stated, conventional LCA does not differentiate between today's emissions and future emissions. (even though the occurrence time of emissions are known, e.g., using the service lifetime of construction products, the conventional characterization factors eliminate the temporality of LCI.) This fact implies that LCI data represents average values throughout the lifecycle of a system. However, while some parameters need to detail their time variability at hourly or daily time step because of its high dynamics, others are variables at large time scales by the order of several decades such as infrastructure or climate condition. Besides, energy mix or user behavior have different temporal characteristics between in short and long-term. Therefore, an appropriate time step for data collection depends not only on the nature of parameters but also on the purpose of studies in searching for a compromise between the precision of LCA results and numerical calculation time.

Time-dependent characterization methods

In addition to time disaggregation of environmental burdens, chemical substances emitted into environmental compartments (air, water, soil) evolves. The climate fluctuations are evaluated by the different effects such as the warming of atmosphere, glacier retreat, and sea level increase. The concentration of greenhouse gases retains radiative forcing in the air, and the Global Warming Potential (GWP) is the consensual metric for evaluating climate change impact category by traditional LCA. The model of GWP returns as output a single score to calculate equivalence of any chemical substances to CO_2, while concentrations of substances are time-variable with complex dynamic physical models. Impact assessment with time-variable environmental models is, therefore, more adapted than conventional characterization factors (CF).

2.2.3 Tools for LCA of buildings and their limitations

LCA is usually performed with dedicated software (e.g., SimaPro, Umberto, GaBi) and inventory datasets (e.g., ecoinvent, ELCD, Agribalyse). There are many LCA tools, software, and databases adapted to the construction sector; several tools that were available for this work and were included in the new methodology are presented here. In France, national experimentation is presently on progress to assess the feasibility to support the future French energy and environmental regulation (called « RE2020 » - *Réglementation Environnementale des bâtiments neufs*, that should be available by 2020) by the LCA method with its public inventory dataset for the construction sector (http://www.batiment-energiecarbone.fr/fr/).

For example, ELODIE is one of the French LCA tools specific to buildings connected to INIES (http://www.base-inies.fr/iniesV4/dist/consultation.html), a public database of environmental and health data for construction products and building equipment. It includes the Environmental and Health Product Declaration (EHPD: FDES in French) and PEP ecopassport® (INIES, 2019). The data recorded in the FDES are values for environmental impact indicators declared in a voluntary way by the industrials. Data sets from INIES provide more realistic and precise information for construction products than other generic LCI such as data form ecoinvent. One constraint of FDES to effectuate dynamic LCA is that it does not contain inventory data (i.e., substance emission flows).

Another French LCA tool for buildings, named EQUER, can be linked to a dynamic thermal simulation tool named COMFIE. This software allows time-varying energy production mixes and energy consumptions to be taken into account when assessing environmental impacts of building energy use at each time step, with historical weather data. As mentioned by Lasvaux (2012) summarizing principal building-LCA software and its databases, many other examples of similar LCA calculation tools for buildings exist in different countries, e.g. One Click LCA (German), ATHENA (Canada), IMPACT (United Kingdom), which are based on different guidelines and contextual hypotheses (methodological choices, boundaries of an evaluated system, method of impact calculation, etc.). For example, LEGEP is a tool for LCA of buildings developed in Germany (LEGEP, 2019), and it has an inventory dataset of more than 6000 construction materials (consulted in April 2019) complying with the European standard EN15804 (CEN, 2012b) defining the method of an environmental assessment of construction products.

Ecoinvent is the most general and widely used in the European area (Wernet et al., 2016) and implemented in many of LCA software. The current version of econivent database is version 3, and it provides over 14,700 LCI datasets as background processes covering the wide range of human activities such as agriculture, forestry, manufacturing, transport, etc. Nowadays, ecoinvent is used for LCA, EPD, carbon footprinting, and other environmental studies.

Energy consumption during the service life can be calculated using models and software developed for thermal performances of buildings. COMETH, the calculation engine for the simulation of a whole building's thermal performance, could be used to compute energy consumptions related to heating, cooling, domestic hot water, lighting and ventilation at an hourly time step (Haas and Corrales, 2014). The tool is compliant with the French thermal regulations. This engine is easily configurable and allows to set the simulation boundary conditions, such as weather or occupant behaviour, and the building description, such as geometry, level of thermal resistance of its envelope and energy efficiency of the equipment. The output of COMETH can be then used as an input in ELODIE - LCA software. The modelling can be effectuated by different interfaces connected to this engine. Some of these interfaces are complying with the future environmental regulation RE2020 (http://www.batiment-energiecarbone.fr/fr/evaluation/logiciels/) (Bâtiments à Énergie Positive et Réduction Carbone, 2019)

None of these tools, however, considers any time-varying characteristics of construction products and equipment in the LCA study, nor can they differentiate the environmental interventions (emissions, resources) over time. Moreover, these existing tools do not allow for dynamic impact evaluations, e.g., the evolution of radiative forcing with time for climate change impact evaluation. This is because the dynamic impact calculation needs data of substance emission flows that is hardly available in specific LCI databases of the building sector.

To the best of our knowledge, there are no LCA tools specifically dedicated to buildings that include dynamic aspects. Only the "New Energy Externalities Development for Sustainability (NEEDS)," in the field of energy production at national and Europe level, includes a dynamic aspect in the form of future electricity supply systems (Frischknecht et al., 2009). Moreover, several scenarios are proposed for the European energy mix by 2025 and 2050, which could be considered in a temporal perspective in order to assess the influence of the grid mix evolution on LCA results.

2.2.4 Different ways of considering time in LCA of buildings

Scheuer et al. (2003) mentioned that future LCA studies should attach more and more importance to accounting for i) change in demand for materials and energy, ii) technical performances of energy services and equipment, and iii) material burdens due to changes in the foreground system e.g. choices of material, service lifetime of building components, as well as in the background system, e.g. production efficiencies of building materials. While authors have argued their proposals to integrate these dynamics in LCA, they did not have access to operational calculation tools to implement them in an appropriate LCA framework.

Frijia et al. (2012) investigated the contribution of manufacturing and construction phases to the life cycle energy use. They proposed different functional units for a residential building, including all domestic functionalities or only heating and cooling systems, to calculate the operational energy use. They also assumed, in their case study, annual improvements in the energy efficiency of heat pumps and air conditioning systems towards 2052, based on public data from the U.S. Department of Energy and periodic replacement of HVAC (Heating, Ventilation, and Air-Conditioning) systems by advanced technologies. Their LCA case study of residential houses revealed that, using an adapted functional unit, which only included heating and cooling systems with a consideration of technological improvement, the share of embodied energy use could be far higher than in previous studies, which were based on the conventional functional unit.

Collinge et al. (2013) proposed a dynamic LCA framework integrating the temporal variability of industrial processes for energy production and the influence of time on climate change impact calculations. The development of their dynamic LCA method was based on the conventional matrix-based computation of LCA (Heijungs and Suh, 2002) and consisted of calculating the inventory and impacts by time periods, i.e., a scenario approach. The functional units and reference flows were considered as parameters that could vary with time from one period to another. They exploited existing public data on dynamic energy productions (time variations of the grid electricity mix), and consumptions and related environmental interventions to obtain a distinct LCI per time period. Temporal variations of processes in the background system (energy production industry) were considered, as were different shares of energy resources over time (the supply chains). The building use phase was studied with particular attention due to the important environmental impact generated by energy consumption in this phase. Time-adjusted global warming potentials (TAWP) were used to calculate climate change impact following Kendall's method of time horizon correction (Kendall, 2012) and using seasonal characterization factors for photochemical ozone formation (Shah and Ries, 2009). This work brought out the importance of considering time in LCA of buildings. However, access to the specific building data (e.g., energy consumption, emissions) and the separate collection of inventory data for many periods might be the main limitation of their work.

Fouquet et al. (2015) performed a comparative study of the static versus dynamic LCA for three low-energy buildings: 1) concrete cavity wall, 2) concrete double wall and 3) timber frame. This study also addressed the relevance of accounting for a temporal profile of CO_2 balance through the uptake due to the growth of trees until the release into the atmosphere at their end of life (Fouquet et al., 2015). The scope of the CO_2 balance should be well defined by considering forest management (i.e., timing of CO_2 uptake) and waste management scenarios at the building end-of-life (i.e., landfilling or incineration of woods leading to emissions of biogenic carbon dioxide), which would lead to significant differences in the results calculated for climate change impact. Scenarios of grid mix were considered at time horizons of 2025 and 2050 based on given prospective LCI data sets from the ecoinvent database and the publicly available database, NEEDS. They also paid particular attention to possible technological innovation in the background system related to cement production using improved production technology. Time-dependent CFs were used for climate change impact calculations, following the method proposed by Levasseur et al. (2010). With this specific case study, it was acknowledged that dynamic LCA could alter the conventional interpretation of LCA results, thus providing a better understanding of the environmental behaviour of building systems.

Electricity consumption and the method used for its production exhibits marked temporal variation in both the short term, e.g., due to daily occupant behaviour or weather conditions, and the long term, e.g., due to the increase in renewable energy technology in electricity mix production, and due to climate change. Integrating renewable energy and auto-consumption systems in buildings, e.g., a photovoltaic system on the roof, requires a more detailed analysis of LCI data over time (Fouquet, 2015). The high temporality of this energy aspect has always been considered in LCA studies. Peuportier and Herfray (2012) developed a dynamic and prospective LCA model to exploit historical data on public electricity (provided by Electricity Transmission Network) differentiated in given time steps from an hour to a year. Energy consumptions of testbed buildings were obtained at hourly or monthly time steps and then injected into the LCA study based on EQUER software in order to evaluate global warming potential (GWP). The impact was calculated by multiplying environmental emissions at each time step (from the French electricity grid) by the corresponding characterization factor (for instance, $CF = 1\ kg\ CO_2\ eq\ /\ kg\ CO_2$ for carbon dioxide). The dynamic electricity production mix model was based upon time-varying productions for each fuel type and based on a given atmospheric temperature. Following this study, Roux et al. (2016b) improved the approach by integrating a temporal variation of local energy production by the on-roof photovoltaic system. The improved methodology was applied to testbed cases of three low-energy buildings to evaluate their environmental performances and acknowledged the discrepancy between static and dynamic LCA results. The time step of the LCI model concerning the energy consumption and production was considered as a key element for the relevance of dynamic LCA results and should be adapted to each case study with respect to local conditions (e.g., climate, energy equipment, occupant behaviour). However, this study was limited to only one year for the energy use phase of buildings. Nevertheless, these studies have the virtue to include commonly used simulation tools in the field of energy efficiency of buildings in a temporal representation of the life cycle inventory, moving forward with respect to other studies (Babaizadeh et al., 2015; Fesanghary et al., 2012) in which the simulation results of dynamic energy demand are used in LCA in an integrated form, as a single total energy value over the building's lifecycle.

Recently, Su et al. (2017) assessed the state of the art of dynamic LCA for buildings, mentioning that the recent developments lack a temporal consideration of socio-economic parameters (technological progress of building components, occupant behaviour). They also proposed the use of time-varying weighting factors in the LCIA phase. These factors could be used to attribute different weights to different impact categories in order to transform them into a single indicator, e.g. monetizing LCA results to compare systems based on a single end-point impact. However, the authors did not identify the appropriate tools, i.e., models, software, databases or data providers, they expected to use when implementing the proposed approach. Their development remains only a theoretical concept without a concrete application to a case study.

2.2.5 Existent operational tools for dynamic LCA

Dynamic LCA is a research subject since a decade but operational tools for performing reproducible and multiple case studies are still under development. Here, some previous developments are presented for both LCI and LCIA steps.

Dynamic Life Cycle Inventory

The first works proposing temporal inventories dealt only with the foreground part of the lifecycle and were focused on GHG-emission timing of the foreground processes (Cherubini et al., 2011; Ericsson et al., 2013; Levasseur et al., 2010). All these works focused on impact generated by few emissions related to foreground processes, and did not propose a structured model for dynamic LCI. The emissions were "manually" distributed in time thanks to a precise knowledge of the studied foreground system.

Beloin-Saint-Pierre et al. (2014) proposed a method based on a temporal characterization of processes and elementary flows. The time distribution of the LCI is performed by using the convolution operation between the distributions of 2 linked processes. A case study was presented on domestic hot water production (Beloin- Saint- Pierre et al., 2016), applying a temporal differentiation for the foreground system only (energy production/consumption). The authors acknowledged that a huge effort is necessary to provide the necessary information for background system. Pinsonnault et al. (2014) applied this same framework to 22% processes of ecoinvent 2.2 database, for which the authors defined temporal characteristics by sector of activity (e.g. infrastructure, forestry, etc.). The analysis was performed for climate change impact, considered also as a criterion for selecting significant intermediary and elementary flows for calculation. This first model for dynamic LCI calculation lacks however of a clear definition of the temporal characteristics needed for processes, flows and supply chains.

Cardellini et al. (2018) proposed a tool for performing dynamic LCA based on a graph search algorithm combined with the convolution operation between the distribution functions of 2 linked processes, like in

Beloin-Saint-Pierre et al. (2014). The dynamic LCI was coupled with GWP characterization factors for climate change. The approach lacks, however, of a parameterized model with clear reference to process and supply chains functioning, and is lacking a proper temporal database linked to the background LCI, as it is the case for the previous methods.

Dynamic Life Cycle Impact Assessment

Concerning dynamic impact assessments, at this moment, still few metrics were developed. The most studied indicator in the context of dynamic assessment is the climate change impact category. As argued in Section 2.2.2, the non-neutrality of the biogenic CO2 effect is now a subject greatly discussed when considering time discrepancy of its flows between the biosphere and atmosphere. With the typical GWP metric, it has been considered that the effect of biogenic CO_2 emissions from bio-based materials is totally compensated by the same quantity of CO_2 absorption. However, when analyzing long-lived bio-based systems (e.g., building), GWP metric would lead to the misunderstanding of climate change impacts because of time-dependent radiative forcing of gases.

To overcome this problem, Levasseur et al. (2010) and Kendall (2012) proposed the new metrics using time-dependent characterization factors based on radiative forcing of GHGs. Kendall's method called Time Adjusted Warming Potential (TAWP) allows to calculate CFs for climate change impacts in function of time. Nevertheless, this method still is partially based on the principle of conventional CF, i.e., time-dependent CF for a target horizon time are calculated at each time step. The analysis time span of impacts is necessary to be selected.

Another alternative solution is the Global Temperature Potential (GTP) (Shine et al., 2005) that takes into account the timing of emissions and radiative forcing. GTP gives a temperature change due as a climate response to an instantaneous radiative forcing at a chose horizon time, and not to a cumulative radiative forcing as GWP. This metric is more appropriate for policy makings regarding the objective of temperature limitation as it directly addresses the global mean temperature change by each GHG (Boucher et al., 2009). Nevertheless, the same constraint as GWP metric is raised for this indicator, i.e., a global GTP is calculated for a targeted certain point to which the GTP of specific gases is normalized with respect to the GTP of a unit CO_2.

Complete dynamic LCA tools (DyPLCA project)(see Annex I for the detailed model)

A dynamic LCA method was recently proposed, providing adapted calculation tools. Tiruta-Barna et al., (2016) proposed a temporal model for LCI, which considers the complex supply chains and processes that compose the life cycle system, for both foreground and background processes. This calculation tool, named DyPLCA (available at http://dyplca.pigne.org/), delivers the dynamic inventory, i.e., environmental interventions by substance/process and aggregated by substance, distributed in time. The dynamic LCI model can be linked to a conventional LCA database (ecoinvent for instance), which facilitates its use by LCA practitioners. A temporal database is included in DyPLCA, containing the time-dependent parameters of processes and supply chains associated with the datasets existing in ecoinvent 3.2.

At present, the DyPLCA tool can be used in the following ways. 1) The life cycle system can be completely modeled by the user on the DyPLCA web interface with any desired data. 2) An automatic mode allows ecoinvent data sets to be used (including different allocation models). In this case, the life cycle system is first modeled with SimaPro LCA software, then the technological matrix and the environmental intervention matrix can be extracted and uploaded within the DyPLCA tool (embedding the complementary temporal database).

Whatever the mode of use, the results provided by DyPLCA as environmental interventions distributed in time are then used with adapted LCIA dynamic models. Currently, there are very few dynamic models for calculating impact indicators in function of time. Global warming was the most considered impact in dynamic approaches. Levasseur et al. (2010) proposed a method based on the calculation of characterization factors (CF) for one-year time step. This dynamic model uses radiative forcing as physical parameter; no fixed time horizon is needed. However, a huge number of CFs calculated for each time step and each substance could be heavy to use.

In Shimako et al. (2016, 2017, 2018), a dynamic climate change model and a dynamic toxicity model were developed and applied with the dynamic LCI to several case studies. In these methods, data and dynamic phenomenological models were implemented: (i) from IPCC (IPCC, 2013) for climate change, and (ii) from the USEtox® 2 model (Hauschild et al., 2008; Rosenbaum et al., 2008) for toxicity impact categories. This approach calculates dynamic impact indicators for any time step, without using a fixed time horizon or reference substance. The models can be directly coupled with the LCI calculator.

The complete framework was successfully tested on case studies by Shimako (2017) and, from now on, it can also be used for building systems. This thesis work is completely based on the tools proposed by DyPLCA. Dynamic LCI model and climate change dynamic indicators are explained in Annex I.

2.3 Presentation of the new approach

2.3.1 General trends from state of the art

While the LCA method is a powerful tool for environmental performance evaluation, the current practice of LCA has not integrated a proper analysis of the environmental performance of systems with a longer time scale, such as building systems. Several of the previous building-LCA studies considered temporal characteristics but limited them rather to the LCI or LCIA steps. Another common limitation of these previous studies is that several temporal aspects are considered only in the foreground system or targeted on a few background processes (e.g., future technological improvement of a particular process). The general temporal behaviour of the supply chains with their time-shifted occurrence is not considered although, on a long lifetime scale, emissions occurring at different time horizons would have very different impacts. Concerning the LCIA step, only a few environmental flows of existing inventory data related to the case studies have been used, most of them just for climate change impact. The existing proposed methodologies lack a general operational method and calculation tools, i.e., software, coherent temporal databases, that could be applicable to any case study.

2.3.2 Identification of key dynamic aspects

Following state of the art, Table 2-2 synthesizes the key temporal aspects that might influence the environmental performance of a building life cycle. Descriptions of the elements are given one by one below.

Type of occupancy. Energy consumption occurring over the whole lifetime of buildings is determined by the typology of occupancy (e.g., a number of inhabitants, age) and the occupant behaviour, among other things. The current practice in building-LCA accounts for dynamic behaviours of occupants only within a year, and occupant behaviours are assumed to be cyclic over the lifetime a building. It is thus relevant to integrate scenarios of occupancy over a long time scale, i.e., evolution of the occupant typology and evolution of the occupant behaviour, into the dynamic assessment.

Building components. Energy consumption levels should also be analyzed with regard to degradations of technical performance of building components, e.g. degradation of thermal resistance of insulation materials over time. Then, considering the future improvement of building technologies and materials, periodical replacement and refurbishment of the building is envisioned with new technologies to satisfy thermal comfort levels and building functions. Although replacement/refurbishment is already included, few previous LCA applications account for technological and technical evolution in time. Insulation materials with higher thermal performances would reduce energy consumption levels, but might need more or less energy and materials in the background system for their fabrication, leading to unexpected changes of the environmental impacts with respect to current practice. For these reasons, it is relevant to integrate potential improvements of technologies and materials into the dynamic LCA at the building component level.

Energy production equipment. The European and French energy and environmental regulations envision an ever increasing percentage of renewable-based energy production, and also the integration of more local renewable energy systems, as discussed in Section 2.2.1. The degradation of the production capacity of existing energy production equipment over time would negatively affect the environmental impacts over the whole life cycle of a building. On the other hand, progress at the level of energy production technologies and equipment could reduce the environmental effects of such systems and consequently of the buildings. After reviewing some previous studies, we propose the integration of technological changes in energy production equipment into the dynamic assessment.

Energy mix. Scenarios of the electricity and district heat production mix on a long time scale should be considered. Renewable energy resources would make up more and more of the grid mix to meet the objective of reducing GHG emissions by energy production systems. Modelling different energy mix scenarios and considering them in building LCA would give a range of variation of results and help to make environmental assessment results more robust.

Biogenic carbon emission and carbon uptake. The current LCIA methods (e.g., EN15978) do not include biogenic carbon (e.g., carbon dioxide emissions from biomass in the GWP calculation) as a factor of climate change. However, as mentioned by Fouquet et al. (2015), for a building composed of significant amounts of wood, it is relevant to take all flows of CO_2 from the tree growth phase (CO_2 uptake from the atmosphere) to the end of the life of the building (CO_2 emissions into the atmosphere). Carbon that is sequestrated in wood during tree growth would be released into the air through the combustion or degradation of wood-based materials at the end of life stage. Carbon dioxide can also be absorbed from the atmosphere by materials having a high content on basic substances, e.g., rich on lime. This process is slow and takes place over decades. For these reasons, it is important for a time span large enough for LCI to be included in the scope of the study in order to encompass all these processes, from forestry management to end of life scenarios. A dynamic LCI approach will allow these different processes to be placed on a time scale. Notably CO_2 uptake and emissions will be separated by long periods of time (e.g., more than 100 years in case of wooden buildings) and no compensation will operate between them (in conventional LCA, CO_2 emissions and uptake take place at the same time and, being of opposite sign, they compensate each other when summed up in the inventory step). This will have a significant influence on the results for climate change impact, in contrast with conventional LCA.

End of life technologies. There are many kinds of technologies for waste treatment at the end of the life of building components and the building itself, depending on the nature of waste (e.g. inert waste, dangerous and non-dangerous waste) and the type of materials present in the waste (e.g. concrete, wool, plastic, etc.) (Bordebeure, 2017). After long lifetimes of several decades to 100 years, end of life technologies and related infrastructures (e.g., recycling processes, energy production mix) will probably have evolved with respect to current technologies. The current practice of LCA can take into account prospective improvements in technologies into the calculation of inventory data. However, ignoring time lags of emissions between the construction and the end-of-life phases, as performed in conventional LCA, would bias impact calculations, especially for climate change impact, by compensations (as explained above for the case of biomass) or by the instantaneous and simultaneous emission hypothesis.

Table 2-2: Identification of key dynamic characteristics of a building system to be integrated into an LCA study

Temporal aspects	**Dynamic characteristics**
1. Occupant behaviour scenario	• Typology of family • Presence time of occupants • Thermal comfort level
2. Construction products	• Degradation of technical performances of building components • Replacement and refurbishment with new technologies
3. Energy equipment	• Integration of renewable energy systems • Deterioration of the production capacity of energy equipment
4. Energy mix scenario	• Modifications of energy mix (electricity and heat) in the long term, based on national strategies
5. Carbon uptake and emissions	• Carbon uptake during the growth of trees • Carbon uptake by construction products • Biogenic carbon emission at the end of life
6. End of life technologies	• Improved recycling rate or energy recovery can be integrated

2.3.3 Proposed methodology for dynamic LCA of buildings

In the building sector, temporal characteristics of systems can be summarized at three levels: building technology level (e.g., technical performance degradations and technological innovations), end-user level (e.g., occupant behaviour) and external system level (e.g., infrastructures, energy mix). These characteristics are represented by time-varying parameters of buildings explained in the previous section and Table 2-2, and should be integrated into fore- and background parts of the inventory. Many of the time variable parameters considered in the present framework are related to technologies and materials of building components, which contribute significantly to the total impact of a building system. On the other hand, dynamic energy consumption and energy mix evolution with technological breakthroughs related to renewable resources and energy management systems (energy storage, smart grids, etc.) are also important contributors. This is because the impact of energy use during the building operational phase depends greatly on the energy production technologies (the background system in LCA).

The proposed methodology for dynamic LCA of buildings relies on the dynamic LCA approach and tools developed by DyPLCA project and presented in Section 2.2.

Figure 2-4 shows the general framework for dynamic LCA of buildings.

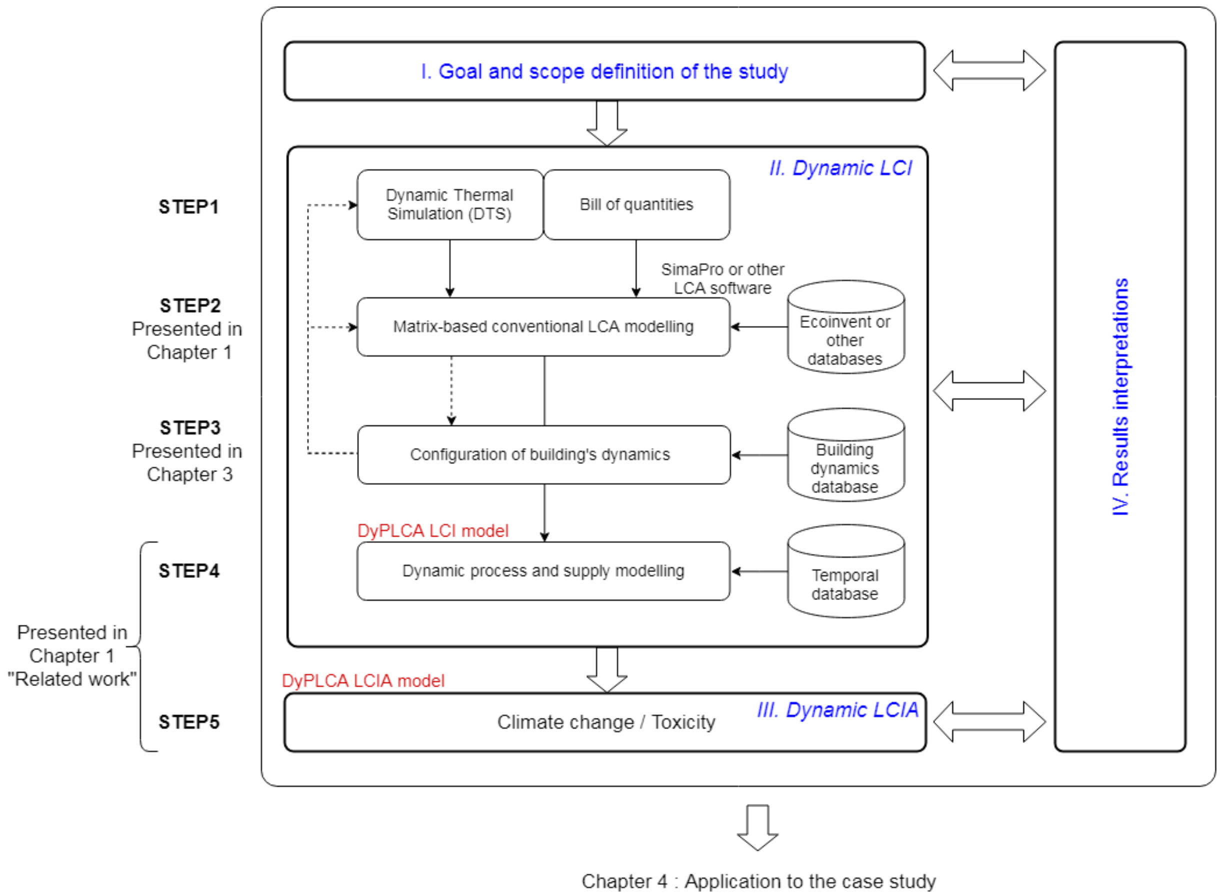


Figure 2-4: Framework of the dynamic LCA methodology applied to buildings complying with ISO 14040 – 14044 standard

Step 1 (Data calculation and collection): Annual energy consumption at the level of a building can be calculated with different time steps, e.g., hourly or daily, thanks to a dynamic thermal simulation tool. COMETH will be used in this methodology as it allows to easily take into account long-term temporal changes in the design of the building's thermal model (boundary conditions based on French data and physical properties of the building). In parallel, data of the reference flow of a studied functional unit should be collected, including product and equipment names, quantity and service lifetime. For example, 20 cm of mineral-based insulation materials for 160 m², whose service lifetime is 30 years, satisfying a thermal resistance level for a whole building with respect to the French national thermal regulation.

Step 2 (Static model of the life cycle system): The building life cycle system could be modelled in SimaPro LCA software or other LCA tools following the conventional matrix-based LCI calculation, with energy and material balances calculated and collected in the first step. The different life cycle stages are identified with different associated activities. For example, the usage of the window's glazing should appear in the phase of construction and also in replacement or renovation phases. Thus, this process appears repeatedly in the life cycle system, but at different moments in time, which will be determined in step 4. For specific modelling in the sector of buildings, data sets from other sources can be used, e.g., FDES. However, despite the advantage of more building-specific content, the use of FDES is currently hampered by the form of the information contained, i.e., the lack of elementary flows. Concerning the foreground part of the life cycle system, any data set (collected on site, modelled, from specific databases) can be used, as is currently done in static conventional LCI modelling.

Step 3 (Dynamic model of building system): This step introduces the temporal dimension in the system modelled in step 2. The key dynamic parameters described in Table 2 are considered. Technological change of construction products and energy equipment will mostly be considered. For example, a renovation of the wall would use new insulation materials. Therefore, this evolution of thermal resistance of a building's envelope would first affect the energy consumption level. Secondly, the material balances of advanced technologies used in renovation should be different from those used in the construction phase. This means that the technological and environmental matrix of the inventory both for fore- and background systems should be recalculated to account for time-dependent scenarios. With this in mind, a database of the temporal behaviour of buildings, "building dynamics DB" in Figure 1, will be developed together with an interface. This database will contain dynamic and prospective parameters of building components (e.g. degradation rate of thermal resistance of insulation materials over 25 years), energy mix (e.g. future proportions of electricity generation resources), occupant behaviour (e.g. potential future change of occupancy profiles), or regulations (e.g. management of specific materials) that can potentially modify the datasets of technology and environment matrixes in conventional LCI databases. Moreover, the database will contain ranges of variation of those parameters, allowing to further investigate the uncertainty on the results. With respect to actual data sets of LCI, such as ecoinvent, that are founded on static or averaged inventory values, the objective of the building dynamics DB will be to account for dynamic and prospective aspects of a building system in a consistent way for all building-LCA studies. An interface making a connexion between a building's LCI previously modelled in Step 2 and the building dynamics DB would greatly help to update LCI with scenarios of a building system over time.

Step 4 (Dynamic model of the supply-chain): Technological and environmental matrix, created from the model in SimaPro or other LCI calculation tool, is then used as input to the DyPLCA tool. DyPLCA contains a database of temporal parameters associated with processes in ecoinvent 3.2, useful for the LCI temporalization of the background processes and supply chains. The building, with its three stages, i.e., construction, use and end of life, represents the foreground part of the life cycle system. The temporal characteristics of the foreground (processes and supply chains) are defined by the user; for example: construction takes 11 to 13 months (Commissariat général au développement durable, 2012) before the building operation phase starts, considering that there is no time lag between the end of construction and the beginning of the building operation phase; renovation of floors occurs after 50 years and takes several months, etc. The output from DyPLCA is environmental intervention flows (e.g., kg/day) according to time (in csv format).

Step 5 (Dynamic model of the impact assessment): Using the temporal discrete LCI (output from DyPLCA), temporal indicators for environmental impacts will be calculated. As mentioned before, dynamic climate change (radiative forcing (RF), cumulative radiative forcing (CRF), and global mean temperature change (GMTC)), human toxicity, and ecotoxicity are the impact categories for which dynamic models have been implemented. In addition, the inventory can also be used for classical impact assessment by calculating the partial or total integral of the flows over time. For the climate change impact category, the model description is given in the next Section 2.3.4.

Figure 2-5 presents in a very simplified manner the life cycle of a building placed on the time scale, with its different stages: construction, use, refurbishment, and end of life phases. Various processes are involved in these foreground stages, each of them with raw material extraction and processing steps in the background part of the life cycle system. Energy production is included in the background as well. The present time (or time zero) can be placed anywhere on the timescale following the user's convenience: the study can be wholly prospective (building in the future), retrospective (building in the past), or building at its different stages in the present time. Dynamic LCA can thus differentiate between past, present and future environmental impacts generated. Each process entering the life cycle at a given point in time can be specific for that time (obviously, if data exists).

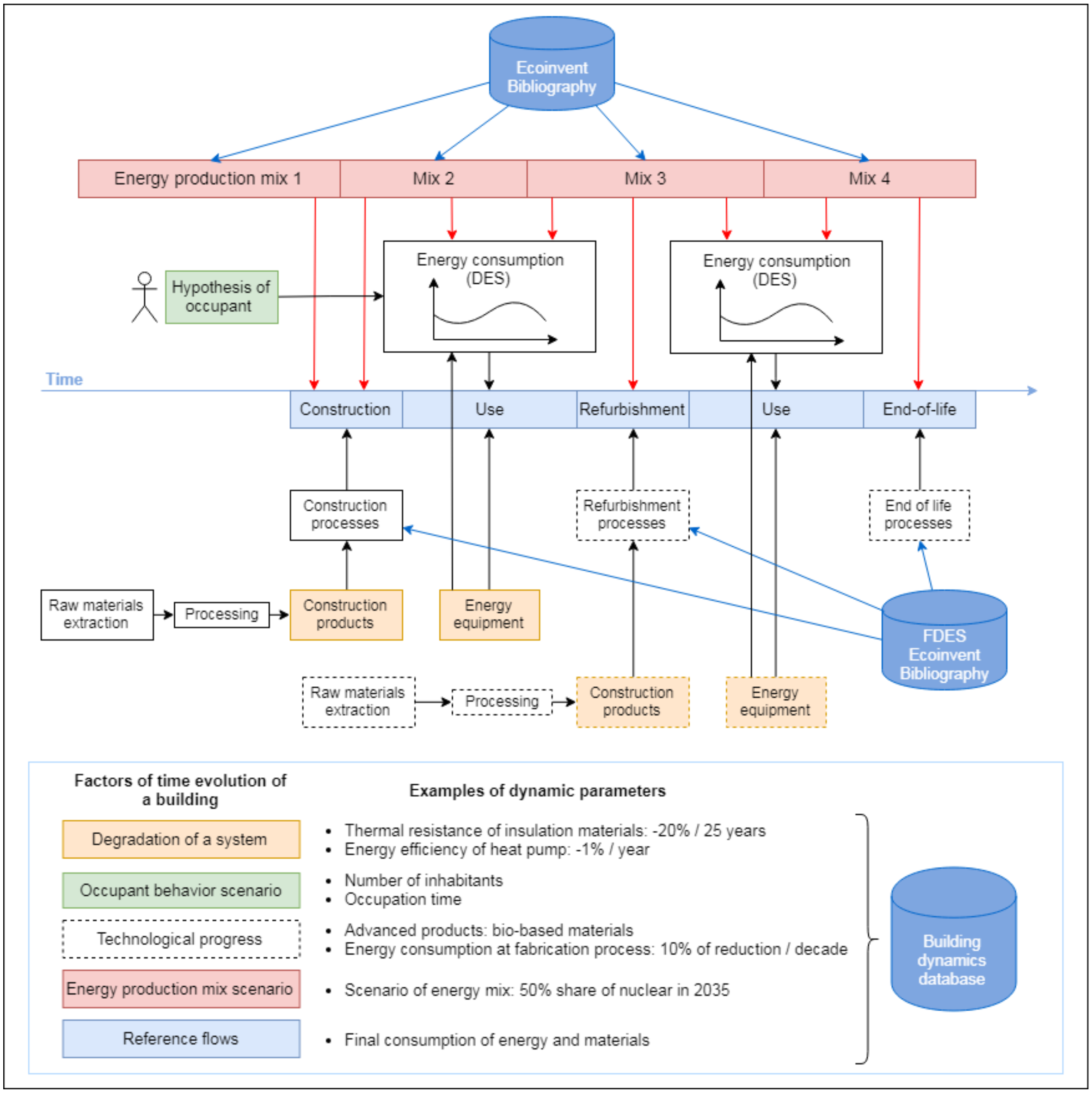


Figure 2-5: Time dimension of a building system and methodological application

The different tools specific for the building are also placed on the scheme. Inventory data for building-related processes comes from databases like FDES, ecoinvent or others, and from literature. Inventory data for very background processes (e.g., electricity production) are rather generic and comes from ecoinvent database. These static data are transformed in time-dependent data thanks to the building dynamics DB and then of the DyPLCA tool. Technological and elementary flows of foreground processes are calculated at the process level with the consideration of time-dependent parameters, leading to variable reference flow per process (e.g., decrease of the heat demand in use phase due to climate change, occupancy, etc.). The factors and parameters affecting the time evolution of building (i.e., the reference flows of different processes in the building's life cycle) are collected in the building dynamics DB. These parameters are used with appropriate models for calculation of material and energy consumption at different points in time (i.e., recalculate the technological, elementary and reference flows of processes). For example, processes concerned by degradation of their performances are marked in blue and processes concerned by occupant behaviour in green – both factors being included in building dynamics DB.

As earlier mentioned, energy consumptions of the building are calculated thanks to a dynamic thermal simulation tool - here COMETH software is an example - by taking into account temporal degradation of thermal insulation and energy efficiency of the HVAC system. Considering for example that zero points in time correspond to the beginning of the construction, processes marked on grey in figure 2 are ones for which technological progress can be considered as prospective scenarios. Technological progress can be envisaged not only for building products but also for the HVAC system equipment. The changes in the HVAC system (if known) can be integrated into the simulation of end-use energy consumptions. Furthermore, technological progress can occur in product manufacturing processes, leading to reductions in energy and material uses in the background processes. The energy mix scenarios in the long-term are applied to both end-use energy consumption and energy consumption at the background processes of a building.

After the calculation of specific material and energy flows, the system is modelled as for a conventional LCA using, e.g. the SimaPro software. This modelling includes many subsystems corresponding to periods with a predefined duration, e.g., one year, or 10 years (user-defined values), each period being characterized by constant parameters for all processes involved in the period. In other words, the time scale is gridded in order to define periods of constant characteristics. After that, technology (technological flows) and environmental (environmental intervention flows) matrixes are generated by the conventional LCA software and imported into DyPLCA tool. DyPLCA tool adds temporal parameters for the supply chain and environmental interventions and performs dynamic LCI calculation. The result, in the form of environmental interventions distributed in time, is the used for dynamic impact (climate change impact category, described in Section 2.3.4) calculation with a Python home-made software.

The proposed methodology takes the temporality of processes and value chains composing the life cycle system into account. The expected results, in terms of inventory temporalization and time-dependent environmental impacts, will allow a better understanding of the building system and a more realistic evaluation of environmental performances. However, one of the limitations is that the state of research in the field of methodological development of dynamic LCA does not allow the calculation of all impact categories commonly assessed by conventional LCA since dynamic models exist only for climate change and toxicity categories. A shift in the common LCA practices is needed in order to foster the development of such advanced tools. French FDES, being collected directly from manufacturers, provide reliable LCIA data sets for construction products and equipment but LCI data (technological and environmental flows) is hardly publicly accessible today. Another difficulty in performing an environmental assessment with the proposed framework concerns the data collection of building system dynamics since the dynamic approach is new and data are lacking.

During the long lifetime of buildings, technologies in the field of energy production, waste management or construction products could be improved or innovative technologies could replace the current ones. The limited knowledge on the future implemented technologies induces uncertainties on LCA results whatever the approach, conventional or dynamic. In this regard, the dynamic approach can evaluate the time limit from which the uncertainty rises due to technological changes.

Another source of uncertainty on LCA (conventional and dynamic) results is the quality of inventory data obtained from databases, modelling, on-site collection, etc. Besides these quantitative aspects, common for both LCA approaches, the dynamic LCI calculation presents uncertainties related to the time dimension, i.e., specific dynamic behaviour of processes, duration, and delays in the supply chain. The new database for building dynamics DB (in Figure 2-4) will contain such time-varying parameters and their ranges of variation. Sensitivity analysis allows the identification of key parameters of the systems and allowing simulation of plausible scenarios as well as uncertainty estimation.

Finally, the added value of a dynamic approach lies on the complementary information it brings out which is the temporal distribution of environmental interventions and impacts, enriching as such the conventional LCA approach. More, the integration of time dimension on the impacts' modelling provides a much more realistic result as the "potential" impact in conventional LCA.

Still being under development, the full capabilities of the dynamic approach are not completely known and exploited by now, numerous case applications on different fields of activity being necessary to this end. In the field of buildings, it could help to define mitigation strategies, as for example: i) possibility to intervene in the future on a given system to avoid/diminish emissions/impacts; ii) possibility to schedule processes in order that their temporality decreases the impacts – for example on climate change the intensity of the impact depends on the emission profile (high pic or flat step); iii) choosing between materials - biogenic carbon versus fossil one, management of biogenic carbon in time in order to favor its capture previous to its utilization, etc. Scheduling the carbon emission and capture is a very important dynamic aspect which greatly influences the climate change impact result.

2.3.4 Dynamic methods for climate change impacts assessment

In this thesis, our impact assessments for climate change impacts are based on the models proposed by Shimako (2017) for instantaneous radiative forcing (W/m^2), cumulative radiative forcing ($W/m^2.year$), and global mean temperature change (K). Here, these models are briefly described.

The radiative forcing (RF) is defined in the 5th IPCC report as *"the change in the net downward flux (shortwave + longwave) at the troposphere after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding other state variables such as tropospheric temperatures, water vapor, and cloud cover fixed at the unperturbed values"* (IPCC, 2013).

The calculation algorithm uses as input the gamma matrix exported from the DyPLCA web application. It requires time span and time step size to be input by the users for the numerical simulation. The above mentioned indicators are calculated at each time step and for any time span.

The atmospheric decay of each GHG is characterized by the Impulse Response Function IRF which represents the dynamic environmental response to a unit GHG emission from a system. This function is defined for each GHG (IPCC, 2007). The general equations of IRF and of the unit radiative forcing uRF for the substance k are:

$$IRF_k(t) = a_0 + \sum_{i=1}^{3} a_i * exp\left(-\frac{t}{\tau_k}\right) \qquad \text{Equation 2-1}$$

$$uRF_k = A_k * IRF_k(t) \qquad \text{Equation 2-2}$$

Where a_i are physical parameters characterizing IRF for each substance k, t is time, $\tau_k$is the lifetime of a substance i, A_k is the radiative efficiency of a gas k ($W.m^{-2}.kg^{-1}$), and uRF_k is the radiative forcing ($W.m^{-2}$) for the emission of 1kg of a substance k.

Then, the radiative forcing RF_k generated by an emission g_k is calculated by using the convolution product between temporal LCI as follows:

$$RF_k(t) = \int_{t0}^{t} A_k \ g_k\ (t') \ IRF_k(t-t')dt' \qquad \text{Equation 2-3}$$

where g_k is the emission scenario of a substance k.

There is now an increasing focus on the Global Temperature Potential (GTP), which is based on the substance contribution to the global mean surface temperature change (Shine et al., 2005). The most appropriate metric and analytical time horizon depend on the objectives of studies and on what types of risks related to climate change should be investigated for a particular application.

In the same manner as IRF, the temperature impulse response function IRF_T was introduced to characterize the dynamics of thermal exchanges at the surface of Earth. The IRF_T and the absolute global temperature potential $AGTP$ are expressed in the following equations for 1 kg emitted substance k (Olivié and Peters, 2012):

$$IRF_T = \sum_{n=1}^{n} \frac{f_n}{d_n} exp\left(\frac{-t}{d_n}\right) \qquad \text{Equation 2-4}$$

$$AGTP_k(TH) = \int_{0}^{TH} RF_k(t) IRF_T(TH-t)\, dt \qquad \text{Equation 2-5}$$

Where the constant parameter d_n (year) is the multiplication of the heat capacity of the system and the climate sensitivity, the sum of f_n parameters ($K.(W.m^{-2})^{-1}$) represents the climate sensitivity.

The global mean temperature change, GMTC or ΔT, (K) is then the convolution between the radiative forcing of a given emission g_k, and the IRF_T:

$$GMTC_k(t) = \int_{t0}^{t} \left(\int_{t0}^{t\prime} A_k \ g_k(\mathrm{t})\, IRF_k(t'-t)\, d\mathrm{t} \right) IRF_T(t-t')\, dt' \qquad \text{Equation 2-6}$$

The GWP estimates the cumulative effects of radiative forcing of a substance at the time horizon TH and normalized with respect to the GWP of CO_2. Also, the conventional GTP is the normalization of the AGTP of a specific GHG with respect to that of CO_2 for a fixed time horizon TH. This means that, in the conventional LCIA, the GWP and GTP are used as characterization factors for climate change impact following a unit impulse at time zero. On the contrary, the dynamic LCIA directly uses instantaneous radiative forcing ($W.m^{-2}.K^{-1}$), cumulative radiative forcing ($W.m^{-2}.K^{-1}$.year), and the global mean temperature change (K). All of them allow impact calculation using temporally differentiated LCI, without clinging on a specific time horizon and without using characterization factors nor reference substance.

Figure 2-6 illustrates the flow of calculation of each dynamic metric for climate change impact.

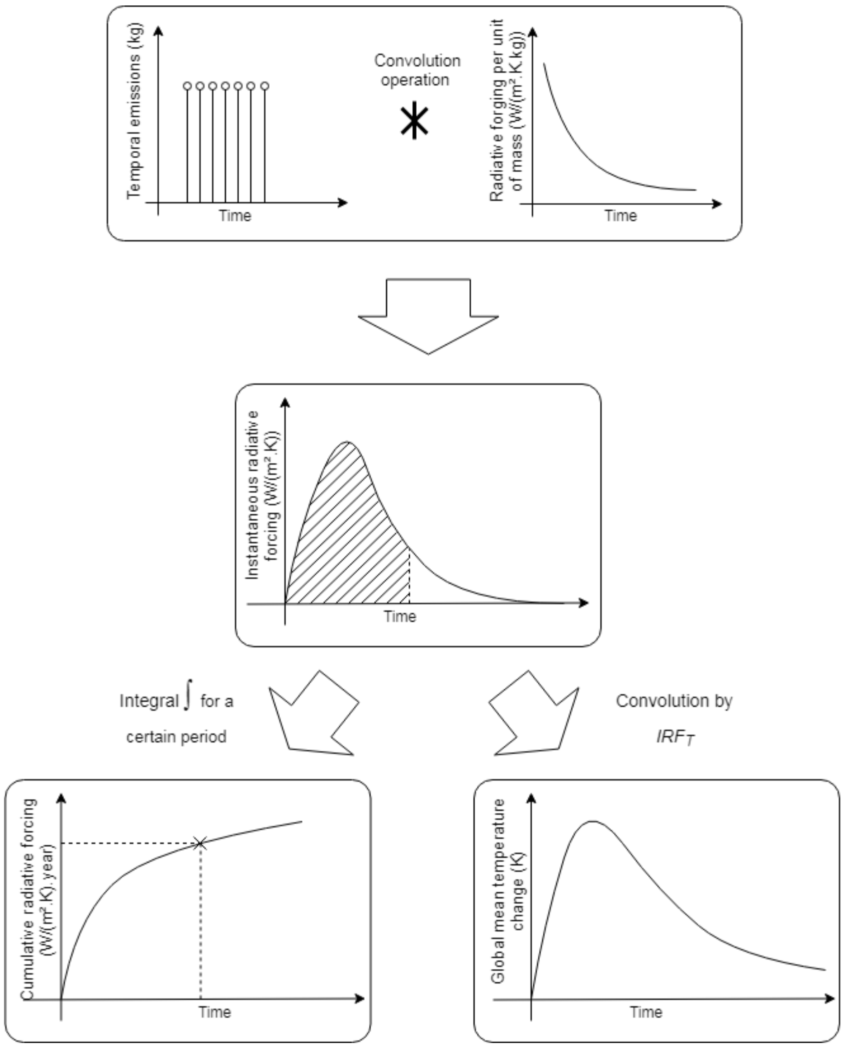


Figure 2-6: Different dynamic metrics for climate change impact

2.4 Conclusion

This study first focused on the temporal characteristics of building systems. Our points of view regarding the time dimension of building systems can be summed up in three levels.

The first is *the temporal evolution at the level of the building* itself. Technical performances related to construction products and energy equipment degrade over the long lifetime of buildings. The occupants of a building are thus required to carry out regular maintenance, replacement, and refurbishment of the building system to satisfy a building function. While the degradation of technical performances of buildings needs to be pointed out, it should not be forgotten that technological improvements of construction products and end-user energy systems should also occur because buildings have a lifetime long enough to take advantage of new technologies.

The second concerns *temporal parameters of the building's end-users*. Changes of occupants and their behaviour (family size, the schedule of their occupation of the building, thermal system management, i.e. thermal comfort level and time of occupants' presence in the house) engender changes in energy consumption and use of building materials.

Third, these previous two types of time dimension should be considered with respect to *change of the background system of the building*. The temporal evolution of the energy production mix, climatic conditions or energy, and environmental regulations are factors influencing not only building technical performances but also occupant behaviours.

In conclusion of the literature review, a building system is a long life system which evolves in time and for which environmental performance is difficult to assess given the limitations of the commonly used environmental assessment tools. The LCA method has been extensively used for evaluating the environmental impacts of buildings, but the lack of a temporal dimension constitutes a considerable limitation. Very few studies have addressed this question so far. Most temporal LCA studies have considered prospective scenarios of technological improvements in fore- and background systems (e.g., energy efficiency of a heating system and cement production) and occupant behaviour (e.g., heating system management) in the long term. Only case studies based in France and the United States have been presented. One study integrated short-term variation of the energy mix composition in LCA, while another showed that it is important to take biogenic CO_2 balance into account over the life cycle of wood-based buildings. The few studies performed so far concerning the building system and its temporal behaviour have proposed an improvement of LCA, which can go beyond the current state of LCA research. However, they do not offer any operational, reproducible tools for performing effective temporal evaluations.

In the present work, we propose a new framework for dynamic LCA applied to building systems. This new methodology represents the complete temporal approach for environmental assessment in the building domain. The framework integrates the time dimension at the level of different steps of LCA.

The life cycle inventory combines an existing environmental dataset for the background processes (ecoinvent v3.2) and LCA software with a new database enabling temporal behaviours of the building system to be parameterized considering technology, occupants, energy mix, and regulations. The DyPLCA tool enables temporal characterizations of processes and supply chains at the background level and for the foreground processes with user-defined temporal parameters. The calculated temporalized LCI is then used in LCIA step to calculate time-dependent environmental impact indicators, i.e., for climate change and toxicity categories. To integrate more specificities of the construction sector, using existing tools and a database specific to the LCA for buildings, e.g., ELODIE (software using FDES as input data) and INIES in France, would help to make dynamic LCI modelling of buildings more case-specific. However, the implementation of dynamic LCA with these specific tools is still limited due to a lack of basic information like the elementary flows or too high a degree of data aggregation. Therefore, the next methodological improvement challenges of dynamic LCA for buildings are the exploitation of FDES data to be used in a dynamic LCI calculation, e.g., the inclusion of detailed information on inventory data, and the development of a tool to calculate a dynamic LCI based on FDES.

The present methodology could be applied to building case studies and, besides providing the impact results, would enable the concomitant development and enriching of the database of dynamic parameters of the building system. However, there is also a need to investigate the sensitivity of LCA results with respect to dynamic parameters for a deeper understanding of dynamic impact behaviours. Identifying the most influential dynamic parameters of building systems could be useful for model simplification and as a guide for applications of dynamic LCA for buildings. Finally, improvements will be brought up by case studies, and the existing tools will be adapted and upgraded for building systems.

Chapter 3

Collection of time-varying building parameters and prospective scenario for dynamic LCI calculation

3.1 Introduction

Today, sustainable building design including environmental, energetic and economic concerns is led by retrospective, static and linear system paradigm. However, as seen in the previous chapters, the building system is indeed dynamic, non-linear and it may benefit from a more prospective approach. Chapter 2 pointed out some key dynamic features to be integrated into the LCA of the construction sector based on previous studies. These dynamic features have the potential to change LCA results and decision makings as seen in (Pehnt, 2006; Fouquet et al., 2015; Sohn et al., 2017). However, the number of distinct dynamic parameters studied within those previous works were still limited. Furthermore, they were all "case specific" because of the lack of any generic operational tool or database that would automate dynamic LCI.

In order to fulfill this gap, the development of a database collecting time-varying building parameters of a whole building system was initiated during the research internship of Denise ALMEIDA (from the April to September in 2018) in the frame of her final project of the graduate school (Almeida, 2018). The development of this database is a part of STEP3 of our methodology of dynamic LCA for buildings as described in Figure 2-4 in Section 2.2.3.

This chapter aims to introduce the collected time-varying building parameters based on the literature reviews and some expert opinions regarding the following questions:

- What are time-varying building parameters that influence LCI (reference, technological, and environmental flows);
- How do they evolve over a long lifetime of a building?

Data is being collected in a matrix format on an Excel file highlighting time-varying building parameters. Each parameter is described by its temporal characteristics such as the time step of variability (e.g., hourly, daily, yearly, decade), and a model of time-varying building parameters (e.g., measurement, prediction, physical model). Once the data has been collected, the next step is to integrate it into LCI modelling. We discuss how to interpret each parameter in order to bring quantitative modification into the LCI model. This modification of LCI due to the parameters can be realized through modifications of a reference flow within the foreground system, or in technological and environmental flows within the background system (see Section 3.2.1 for the definition of fore- and background system).

As an example of change in a reference flow, a change in the number of occupants is interpreted as a change in household energy demand as the human body is accounted as a heat source (Oldewurtel et al., 2013). Therefore, different scenarios of occupants modify heating and cooling energy demand, and can be calculated by dynamic energy simulation of a building.

Meanwhile, the technological innovation of certain materials would bring changes not only in the reference flow but also in material and energy balances in the background system (certain points in the production and supply chain). Such change is implemented through a modification in technological and environmental flows within background processes.

This chapter also studies the aspect of time lag consideration related to the foreground processes in a building system (i.e., temporal parameters: time lags related to activities of the construction, maintenance, replacement, demolition, and waste treatment). Once an LCI with the building's dynamic aspects is established, this updated LCI is coupled with the DyPLCA method and tool that allow distributing LCI over time through the network of the production and supply chain (see the method in detail in Annex I and Tiruta-Barna et al., (2016)). A search algorithm runs through the network structure of a studied system to trace each emission and their time of occurrence. As previously mentioned, temporal parameter for background processes is defined by default thanks to the DyPLCA temporal database, while one needs to set temporal parameters of foreground processes.

In order to facilitate the understanding of lectures of the thesis, we distinguish from now on the two following terms: "*time-varying building parameter*" that characterize the physical evolutions of building systems over time and "*temporal parameter*" that characterize the network of production and supply chain over time.

The subjects discussed in the chapter deal with the second step in the framework of dynamic LCA: dynamic LCI calculation, as shown in Figure 3-1.

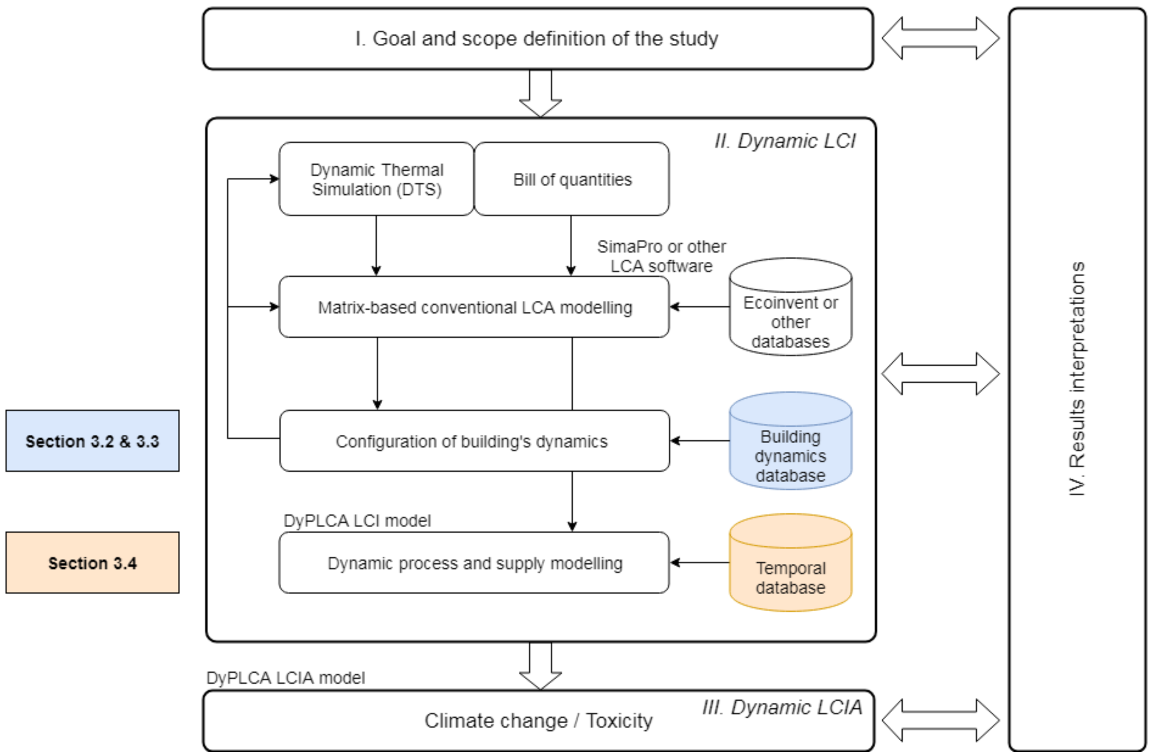


Figure 3-1: Temporal aspects discussed in the chapter

Section 3.2 presents different natures of time-varying building parameters of building systems in order to classify them and facilitate the data collection. Those parameters are broadly divided into three levels: *building technology* (e.g., a technology of building materials), *end-user* (e.g., socio-economic behavior), and *external system* (e.g., energy mix, climate conditions, etc.) as briefly introduced in the conclusion of Chapter 2 (Section 2.4). At the end of this section (3.2.4), the list of time-varying building parameters collected for the moment is introduced.

In Section 3.3, we will present in more detail some categories of collected time-varying building parameters of which the temporal characteristics (e.g., type of parameter, a model of temporal evolution, the time scale for scenario developments) are examined in the database.

Section 3.4 discusses one particular part of the dynamic considerations related to the production and supply chain dealing with DyPLCA method to make temporalized LCI.

3.2 Classification of the building dynamic parameters

3.2.1 Foreground and background system

In the LCI modelling, there is a method to divide a system into *foreground* and *background* system. To the best our knowledge, the very first publication introducing the concept of this system division is Clift et al., (1994) followed by a working group of the Society of Environmental Toxicology and Chemistry (SETAC) in 1998 and only a few publications (Tillman, 2000; Clift and Druckman, 2016). The division of system in fore- and background does not affect LCA results because it is not an allocation method to calculate process-related LCI and it does not imply the modification of system boundaries. The concept is not a scientifically well-established one, and it is not standardized. However, the classification of processes in fore- or background systems helps to define an important part of the system that may be different in function of actors of decision makings. In a dynamic LCA study, the concept also allows making clear which time-varying building parameters impact are indeed involved in decision making.

In general, the foreground system includes a set of processes issued from the case-specific measure of an investigated system. Foreground processes are thus directly affected by decisions made in the scope of an LCA study. The boundary of a foreground system can be changed regarding different actors for the same system studied (Tillman, 2000). Pinsonnault et al. (2014) gave more explicitly the definition of the foreground processes considering that processes in the first two tiers from a process of the functional unit are the foreground ones.

The background system represents a set of processes, and their technological and associated environmental flows are affected indirectly as a consequence of the change in processes of the foreground system (Tillman, 2000). All processes that are not allocated to the foreground system are considered to be in the background system. As an example of the building sector, from a building owner’s point of view, the choice of construction products is affected directly by the owner’s decision. Thus construction products are defined as a process being in the foreground system. Whereas, all the other technical aspects, such as energy consumption at product fabrication processes can be changed in function of the choice of construction products and it is defined as a process being in the background system.

In the DyPLCA web application, the definition of temporal data (for the delay related to production and supply chain) of background processes is given by the database developed by the project (Tiruta-Barna et al., 2016; Shimako, 2017). Concerning the foreground processes, dynamic LCA users should define temporal data on their own. The definition of the foreground processes of the building sector will be described in Section 3.4.

3.2.2 Physical scale of time-varying building parameters

Time-varying building parameters can also be classified by their physical scale as briefly introduced in the conclusion of Chapter 2. The distinction of parameters at different physical scales does not have any influence on LCA results and any significance in terms of LCA calculations. However, in a same manner as the concept of fore- and background system, the indication of *which parameters are varying in which part of building systems* would help LCA actors to identify hotspot for GHG reduction actions. Figure 3-2 illustrates the different physical scale with some examples of dynamic parameters.

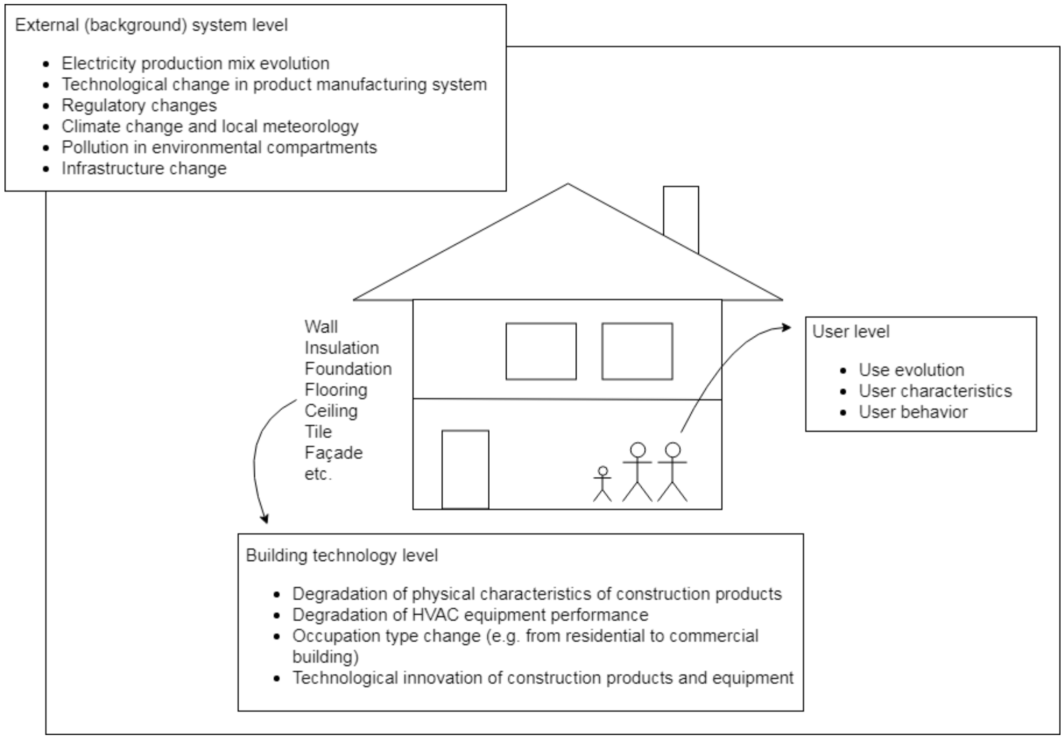


Figure 3-2: Physical scale of dynamic aspects

The time-varying building parameters related to the *building* itself define the technical performances and characteristics of the building's components, construction products, materials, and equipment. For example, the thermal resistance is a parameter that defines a thermal performance of a specific building and is derived from the insulation materials and thermal conductivity, an intrinsic property of materials. The degradation of thermal performance is for example due to weather condition (e.g., humidity) or socio-economic factor such as the rate of maintenance of products. Since the functions of insulation materials (e.g., thermal or acoustic resistance) deteriorate over time, it must be replaced or renovated if its lifetime is inferior to the lifetime of a studied building (CEN, 2012a). As ISO 15686-1 standard defines the service life as "period of time after installation during which a facility or its component parts meet or exceed the performance", the durability of products is defined in relation with its technical performances (ISO, 2011). The longevity of a building implies not only system degradations but also the upgrade of the system, thanks to technological innovations. The integration of the technological innovation strategy into LCA study, in relation to the national and international objectives such as the French Agreements for Green Growth (MTES, 2016), will help to foresee possible future pathways of impacts. Therefore, it will help supporting decision makers towards an appropriate eco-friendly decision.

The time-varying building parameters at the *end-user* level relate in principal to the socio-economic characteristics of the system's user, i.e., building inhabitants in our case. Their behavior and the composition of their family evolve in a various way during the building use phase. The amount of energy consumed depends on the type of presence occupants have at hourly, daily and seasonal scales, but it also on how the thermal comfort level or the technology of energy equipment change over the long time scale. Therefore, this class of parameters influences consumptions of energy and water, as well as the state of the equipment, but directly and indirectly. The occupants' behavior also makes a difference in the state of construction product and materials. With a shallow level of maintenance, products and materials may degrade faster than with regular maintenance.

The time-varying building parameters at the *external system* level are the ones that bring changes in the processes of the system studied beyond a building and its user over a long time scale. Parameters at this scale first generate a modification in parameters at the building and end-user levels, and then, influences the final results of LCA. For example, the mix of electricity production will change in the future with the integration of renewable sources. Then, the impact will be taken into account through a modification of end-user's energy consumption. Regulatory changes are another example that may interfere with the use of a given building, and therefore impact the building's environmental performance. This fact means that the evolution of certain parameters in this class will appear as a change in the intensity of technological and emission flows of a unit process, but not as a change of type of foreground processes involved.

There can be complex interactions between the external system and the building, the external system and the building users, and between the building and its users. However, in the thesis work, the modelling of parameters interactions is not considered in order to simplify our dynamic LCI modelling.

3.2.3 Integration of time-varying building parameters into LCI calculation

Time-varying building parameters involve different elements of the LCI calculation step: the reference, technological, and environmental flows of a system studied. The reference flow is a representation of the final consumption within a given system boundary in order to assure the functionalities of the system (Guinée, 2006). Therefore, the change in the reference flow modifies the environmental impacts. For example, the quantity of ceramic tile for the renovation can vary depending on whether the ceramic tile is well maintained or not during its use. In this case, the maintenance rate or the degradation rate are considered as parameters that directly modifies the reference flow at the LCI calculation step.

The technological flows define the supply chain between different processes. It involves the intensity of unitary material and energy balances relative to a supply chain, and thus associated emissions. For example, ecoinvent data set (Wernet et al., 2016) defines a production process of 1 kg of ceramic tile requiring (among other things) 0.489 kg of clay and 0.313kWh of electricity at the medium voltage level as technological flows. Now, we can expect innovation of the ceramic tile with a lesser need for clay or an energy efficiency improvement of the ceramic tile fabrication process in the future. Therefore, the modification of the technological flows should be brought into the LCI calculation. In addition to this technological flow change, the emission intensity variation over time for a unit production (i.e. the environmental flow) leads to a change in LCA results. For example, emissions into the air due to the burning process of ceramics can be varied in the future if manufacturing process or energy resources change.

Figure 3-3 illustrates the influence of time-varying building parameter with graphical expressions explaining which step of LCI calculation time-varying building parameters are involved in. The points and blanches colored in red represents temporal evolution. To model LCI with temporal evolution, all time-varying building parameter should be expressed as one of the three cases.

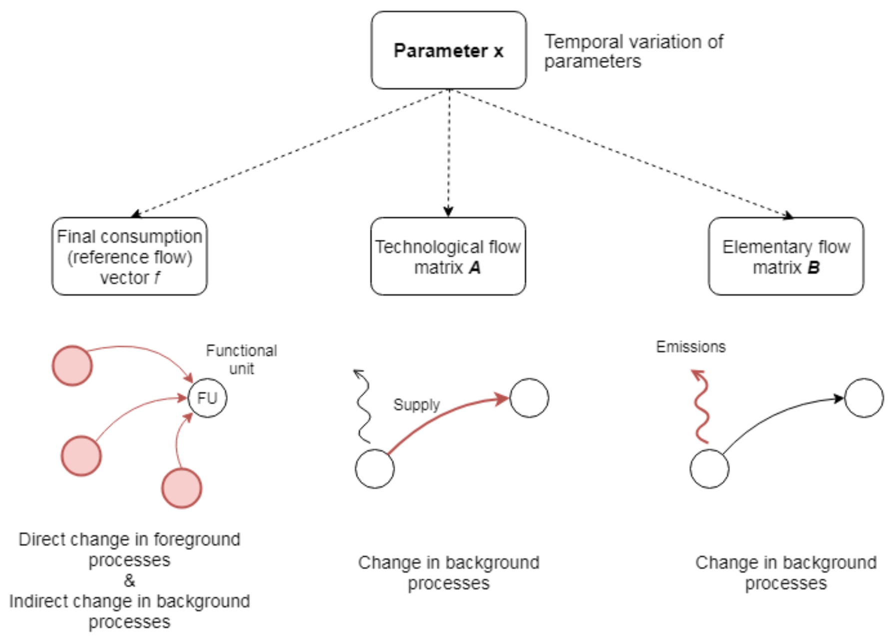


Figure 3-3: Influence of time-varying building parameters on different elements of LCI calculation

3.2.4 Type of data collection

According to the state of the art of time-varying parameters of building systems presented in Section 2.2, we identified several aspects that present relevant temporal evolutions in the different aspects of a building system in Table 2-2.

In Section 3.3, we will present collected data with our special emphasis on the questions raised in Section 3.1: 1) What are time-varying building parameters that influence LCI (reference, technological, and environmental flows)? And, 2) how do they evolve over a long lifetime of a building? With these questions in mind, we discuss potential short- and long-term scenarios of a building system identified from the literature review. Some of these scenarios will be analyzed with the context of a dynamic LCA study for the buildings. Therefore, this section will also illustrate how identified parameters can and should be exploited to develop process-level LCI models incorporating building's dynamic aspects. For each dynamic aspect, some examples of LCI application are demonstrated. However, some of the collected data could not yet be analyzed well enough to be adjusted for their application to LCI modelling. Further work will be necessary in that case. Furthermore, the application of some of the collected time-varying building parameters to a case study will be presented in Section 4.4 for the explanation of scenarios and in Section 4.5.3 for the scenario analysis with dynamic LCA.

There are two ultimate goals of the database development: the collection of time-varying building parameters that cover as many sectors of activities related to a building system as possible and the exploitation of all collected date in order to connect to LCI model. Nonetheless, a building system is composed of a limitless number of dynamic aspects in short, average and long time scale. Such research of dynamic parameters without any method is a time-consuming step and requires a very wide range of knowledge. To overcome this problem, we need to limit the boundary of our research of time-varying building parameter within a building system. Our focuses of data research are introduced in the next paragraphs.

Technical performance degradations

At first, we started the data collection by searching long-term degradation parameters of construction products and household energy equipment, which especially characterizes the level of operational energy consumption. The LTECV (MTES, 2016) takes objectives with a long-term perspective of the contribution of the building sector to the low carbon national strategy. In this context, the OPEN project of the ADEME identifies five products and equipment (windows, walls, roofs, heating and DHW production system) as principal posts to reduce the energy consumption and the GHG emissions through the renovation (ADEME, 2016). Given that the building sector is the most important energy consumer and GHG emitter among different industrial sectors in France, the energy renovation of buildings is identified as one of the pillars for energy transition and savings.

Investigating the influence of technical performance degradation of products and equipment to household energy loads is raised important because it allows not only establishing a long-term emission pathway, but also reinforcing scenarios of GHG reduction at a long time scale (e.g., renovation strategy).

At the same time, we get interested in construction products and household energy equipment having a short service lifetime (inferior to the building's lifetime). The reference lifetime of some products is proposed by the Level(s) project of JRC European Commission (2018). In practice, short-lived products and equipment need to be replaced one or several times during the building's long lifetime. Furthermore, from the LCA's methodological point of view (more precisely, due to the implication of a *functional unit*), they should be replaced when they cannot satisfy any more functional units because of the decrease of their technical performances. The calculation method of the number of replacements for components, products, and materials in a building is defined in the section 9.3.3 of the EN 15978 standard (CEN, 2012a). Taking into account factors to estimate technical performances of components, products, and materials allows for an accurate estimation of the product service life variation. Then, it enables to more precisely estimate material and energy balances, and associated impacts. Modeling of system durability and degradations is a very complex problem as seen in the work of Talon (2006). Our work only focuses on how the maintenance of system modifies the system durability based on available public data.

From the above reflections, the technical performances degradation of insulation materials and windows, the windows service life, and the energy efficiency loss of heating equipment (heat pump, air conditioning system, electric convector, boiler, on-roof photovoltaic system) were first examined in Section 3.3.1.

Technological innovation

At second, we collected data concerning technological innovation. The presence of replacement stresses the emission and the environmental impacts for a long period implicated by the fabrication processes and product waste treatment. And, the replacement at average and long term interval necessarily involves technological innovations for certain equipment (Frijia et al., 2012) and there can be various possible alternative pathways with respect to the environmental impacts. Therefore, accounting for potential gains that can be obtained by technological innovations related to these emissions due to short-lived products.

In parallel, the construction sector presents today a significant amount of waste at the end-of-life of a building (Bordebeure, 2017). In this context, the various national objectives for different industrial sectors with a vision of material circularity are established (MTES, 2016). Therefore, we searched the evolution of recycling rate and of recycled material use in the fabrication processes for products and materials to which the national strategy has recently been set.

Finally, together with the strategy for material recovery and energy savings, the increase of the share of renewable energy sources becomes one of the prominent strategy towards low-carbon electricity (MEEM, 2016). During the thesis work, the future mix data was collected and some of which are integrated into the case study (described in Section 4.4.4).

Table 3-1 summarizes time-varying building parameters of interest. The next sections are dedicated to the collection of data and the explanation of the integration of collected data into LCI.

Table 3-1: Temporal aspects and time-varying building parameter to collect for scenario creation

Dynamic characteristic	Concerned elements	Time-varying building parameter
Degradation of physical characteristics of a material	Insulation material	Thermal conductivity increase
	Window	Thermal resistance decrease / gas leakage rate
		Maintenance rate of components, products, materials
Degradation of equipment performance	Heat pump	Progressive loss of efficiency
	Electric heater	Progressive loss of efficiency
	Gas boiler	Progressive loss of efficiency
	Photovoltaic panels	Progressive loss of efficiency Replacement frequency
Technological evolution	Insulation material	Composition and characteristics of innovating insulation materials

		Thermal conductivity reduction
	Recycled material use	Increase in the rate of recycled content integrated into product fabrications
	Waste treatment	Increase in the rate of end-of-life scenarios (recycling rate / landfill rate/ recycled content of material - if closed loop)
	Electricity mix	Share of each energy source through the years

Available public data may not have a homogenous format. For example, technical degradations can be expressed both as qualitative and quantitative parameters. When it is a qualitative parameter, it needs to be transformed into a quantitative one in order to implement numerical simulations of environmental assessment. Besides, time-varying building parameters directly influence three aspects (reference, technological, and environmental flows) while many of them have an interactive effect between them. For sake of simplicity, we first collect quantitative parameters without consideration of parameters' interactives.

An essential aspect to be considered when collecting data is the data quality. As a building system covers an incalculable number of dynamic aspects, time-varying building parameters can be found from numerous national and international sources. Therefore, it is important to select relevant scientific references. For each parameter found, we will clearly indicate the reference and the type of parameter model (e.g., measurement, experimentation, theoretical model). However, the uncertainty study of the LCA results engendered by the time-varying building parameter is out of scope for the moment, because a dynamic LCA methodology developed here is not enough mature to be applied to the sensitivity and uncertainty analysis. This thesis presents a very first case study of the proposed methodology applied to a building (Chapter 4) and the important role of the thesis is to show the feasibility of the dynamic LCA application to the building sector. Thus, we focus on the discussion about how each time-varying building parameter should be adjusted to model dynamic LCI when it is possible and not how the error of parameters impacts on LCA results.

Nevertheless, the quality of data influences the quality of LCA results and decision-makings. The sensitivity and uncertainty analysis will be discussed as a perspective work beyond the thesis in Chapter 6.

3.3 Time-varying parameters of building systems

In this section, we present only three categories from which time-varying building parameters are collected (insulation material degradation, recycled material usage, and a mix of French energy production) in addition to the way we considered to integrate them into LCI modelling. For simplicity, all other categories are presented in Annex III.

3.3.1 Insulation material degradation

Designing buildings in terms of their thermal performance is essential to save energy and provide thermal comfort to building occupants. As illustrated in Figure 3-4, the building envelopes (e.g., wall, roof, window) are important sources of heat loss (ADEME, 2011). At the same time, as a significant amount of insulation is used to envelop a whole building, the balance of material flows for insulations is important. A different materials insulation technology, present today in the market, has been developed in different forms (e.g., rigid, sprayed, and liquid), shapes (e.g., cavity, filling, and sealing), and applications (i.e., floor, walls, and roof).

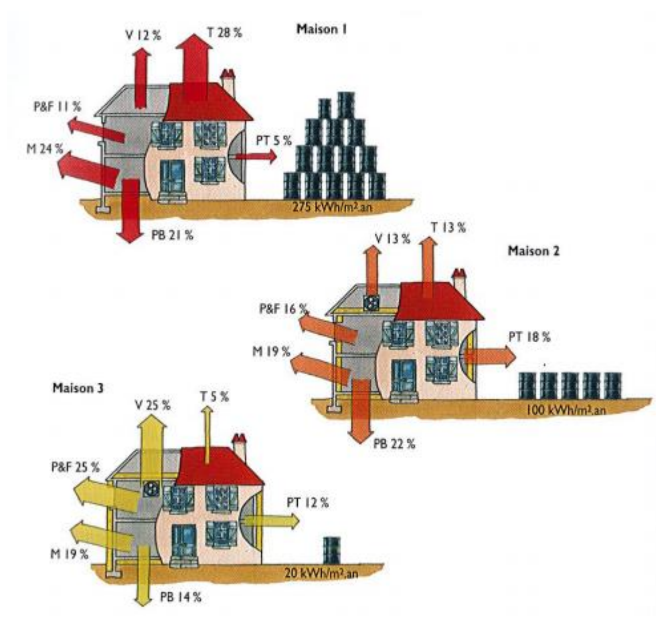


Figure 3-4: Examples of heat losses through the building envelops for different typology of single house (Maison 1:House with 20cm of wall of concrete block, Maison 2: House with 20cm of wall of concrete block and internal insulation at the RT2005 standard level, Maison 3: House with 20cm of wall of concrete block and external insulation at the low consumption standard level) (Olivia and Courgey, 2010)

The thermal performance of insulation materials is characterized by its thermal conductivity λ ($W.m^{-1}.K^{-1}$). λ is the material intrinsic physical property, which specifies the heat transfer behavior by conduction. It is measured by the heat amount that flows through a meter of material per second.

An important parameter to measure the thermal performance of a given insulation installed in a particular building is the thermal resistance (R). It is obtained by dividing the material thickness applied to the building by the material thermal conductivity. Therefore, R value represents the resistance that the material provides to the system under specific conditions. The mass of insulation material can be estimated using the two known physical properties: thermal conductivity λ and density ρ, according to the following equations:

$$R\ (m^2.K/W) = \frac{thickness\ of\ insulation\ material(m)}{\lambda\ (W/(m.K))} \qquad Equation\ 3\text{-}1$$

$$Mass\ (kg) = thickness\ (m) \times 1(m^2) \times \rho(kg/m^3) \qquad Equation\ 3\text{-}2$$

Table 3-2 resumes some publications that discuss the increase of materials thermal conductivity or the decrease of wall thermal resistance caused by material degradation and aging (Stazi et al., 2009, 2014; Choi et al., 2017). They have measured the thermal resistance or conductivity at two distinct time horizons. Lower thermal performance level was found in every case after several decades.

These thermal performances of the insulation materials will be used as a hypothesis for dynamic energy simulation to calculate the household energy consumption over the year (see Section 4.4.1). When the service lifetime of insulation is over, we consider that the insulation materials are replaced. The number of replacements is calculated strictly according to/ based on the EN15978 standard (see Section 9.3.3 of CEN (2012)). We can also formulate the following hypothesis: insulation materials are partially replaced. In this case, the total mass balance required for the complete or partial replacement to compensate for lack of thickness at a given year can be obtained by Equation 3-2.

Examples of application to LCI modelling

Energy consumption can be estimated using a dynamic energy simulation tool e.g., COMETH, in taking into account collected thermal conductivity of specific materials for given years. Then, interpolations and extrapolations (linear or non-linear depending on hypothesis) can be applied to estimate energy consumption at yearly time step. This change in energy consumption deals with the change in reference flow.

Table 3-2: Example of collected data and models of the degradation of insulation materials

Concerned products/materials	Dynamic aspects/properties	Data collection method	Collected data / model	Source	Remark
Expanded Polystyrene (EPS)	Decrease in heat transfer rate	Measurement / Experimentation	Decrease by 25% / 20 years (0.50 to 0.55 W/m².K in 1987 0.38 to 0.41 W/m².K in 2007)	(Stazi et al., 2009)	• This is an experimental study effectuated to insulation materials retrieved from an existing building constructed in the 1970s • Decrease rate varies in function of the side of envelop
Glass wool	Increase in thermal conductivity	Measurement / Experimentation	Increase by 12% / 25 years	(Stazi et al., 2014)	• This is an experimental study effectuated to insulation materials retrieved from an existing building constructed in the 1980s • The decrease of the hydrophobicity of the glass wool is the main cause of thermal conductivity increase
Polyurethane (PU)	Decrease in thermal resistance	Measurement	Decrease by 6%/100 first days Decrease by 20%/1000 first days Decrease by 27%/5000 first days	(Choi et al., 2017)	• This study evaluated the degradation of different types of polystyrene insulation.

3.3.2 Recycling content materials/recycling process inputs and outputs

Actions for promoting circular economy has been increasing in France the last few years, principally due to the importance of this subject in the national agreement of ecological transition for the green growth (LTECV in French). LTECV sets important goals, such as reaching a 65% recycling rate for non-dangerous and non-inert waste and reducing landfill by 50% by 2025 comparing to 2010 (MTES, 2016).

Building and construction are the key sectors regarding this subject. The sectors are responsible for generating 40 million tons of waste by year, 90% of which from demolition and building rehabilitation. For material efficiency and waste management, LTECV sets a goal to achieve a recycling rate of 70% for demolition and rehabilitation wastes in 2020 (FFB, 2018).

In this context, the French government has launched several programs for the most critical products through the so-called "agreement" or "green deals" between the main industry actors for each targeted branch (MTES, 2017). Until now, the target products are flat glass (MTES and MEF, 2017), plasterboard (MEEM and MEIN, 2016a), acrylic glass[2] (MEEM and MEIN, 2016b), inert wastes from buildings and public works (MEEM and MEIN, 2016c). The agreement between flat glass' stakeholders was signed in December 2017 by the Minister of Ecological and Solidarity Transition (in French – *Ministère de la Transition Ecologique et Solidaire* - hereinafter MTES) , the Minister of Finance and Economy and the associations of recyclers and union trades of glass producers (MTES and MEF, 2017). Among all agreements established until now, flat glass is the only product to which a target for increasing the recycled content has been set. The goal at the horizon of 2025 is the shift of the cullet rate as a raw material of flat glass from 30% to 50%.

Moreover, we also found ISOVER's report (2018) mentioning the potential improvement of glass wool recycling. According to the report, the current rate of the recycled material part integrated into the glass wool varies from 40% to 80%. Mineral-based wools (glass and rock wools) have been and still are the most commonly used insulation material in France representing by 49.2% of its total (CSTB, 2017). In this context, the increase in recycled material use of glass wool as primary materials may lead to a significant gain of material and energy use as well as associated impacts.

[2] Acrylic glass is a developing market in the construction sector (Grand View Research, 2017)

Examples of application to LCI modelling

Modification in the quantity of culet as primary material contained in the flat glass is considered for the windows of replacement. It involves the change in technosphere flows in the background system rather than in reference flows.

The existing ecoinvent process of flat glass used for window's glazing does not contain any culet (e.g., *Flat glass, coated {RER}| production | Alloc, Def, U*). Therefore, a new module ecoinvent of window integrating cullet up to 50% of the total mass of flat glass as shown in Figure 3-5. The detailed value of each material is presented in the intern report of Almeida (2018).

However, an important constraint of this model is that we could not consider performance changes due to the insert of cullet. In other words, this new flat glass is considered to keep exactly the same functionalities as the original process model.

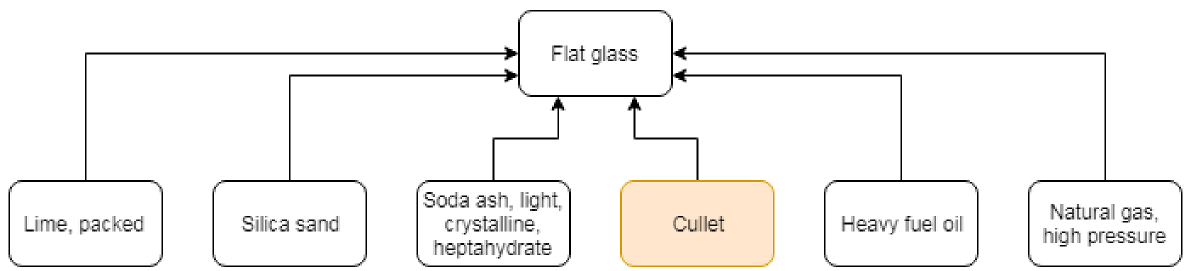


Figure 3-5: Simple description of the ecoinvent model of "Flat glass, coated"and the integration of cullet

Table 3-3 shows the identified current and future rate of recycled material contents for flat glass and glass wool.

Table 3-3: Example of collected data and models of the innovation of the rate of recycling material content into construction products

Product name	Dynamic aspects and characteristics	Data collection method	Data / model	Source	Remarks
Flat glass	Increase of the rate of recycled contents into the flat glass	National strategy	Current: 30% 2025: 50%	(MTES and MEF 2017)	• The green deal agreement for flat glass presents a mid-term goal aiming to the increase of the amount of glass culet incorporated in new flat glass
Glass wool	Increase of the rate of recycled contents into the glass	Measurement	The rate can vary from 40 to 80%	(ISOVER, 2018)	• Current rate of recycled content in the glass wool products is at least 40%, however some ISOVER plants can produce glass wool containing until 80% of recycled content

3.3.3 Future French energy mix

As stated in Chapter 2, the transition of energy load is an important field of study for curbing GHG emissions within an average- and a long-term strategy at national and international levels. In 2018, the European Union set a new target for renewable energy integration within the production systems, at least by 32% reduction towards the horizon of 2030 in order to meet the Paris agreement goals (European Parliament, 2018). This binding objective of increasing renewables aims to cut at least 40% of GHG emissions by 2030 compared to 1990 at the European Union level. Each European country sets its energy strategy in accordance with this European goal. In France, the high penetration rate of nuclear power in the electricity mix already allows a very low carbon intensity per unit of electricity with respect to other countries. Nevertheless, household energy consumption in the fore- and background systems, based on the French electricity mix, still makes up in average 30 to 40% of the total climate change impact through the lifecycle of a building (Lebert et al., 2013).

In this context of energy mix transition, different prospective electricity production scenarios were proposed by several research institutes in France (e.g., RTE, ADEME, ANCRE, négaWatt). French mix scenarios are established in general based on various assumptions related to demography, economy, technology, and regulations. While some scenarios (e.g. RTE) consider previsions at an average time scale of around 2035, others (e.g., ADEME, négaWatt) elaborate scenarios to a longer horizon, up to 2050. Some scenarios are more established on the basis of the future evolution of socio-economic factors, such as demography and consumer behaviors in different sectors. Meanwhile, others (e.g. ADEME) provide scenarios involved in the evolution of technological aspects with respect to the specific objectives of each technological field.

In order to effectively perform an LCA with prospective mix data, it is important to select the scenarios to be collected following a systematic approach method of examination. For example, a working group of SCORE LCA proposed a method of prospective data selection (Querini et al., 2017). They ask a pre-determined set of questions so that LCA users can define their system's prospective pathway for an LCA study. The objective of the prospective study, nature of parameter change (i.e., consequential or attributional), and horizon time of each future mix scenarios are namely investigated.

Our study of the building's LCA is performed during a long time interval (more than 50 years). Therefore, the scenario of the mix in a long time scale may be appropriate. Taking mix scenarios into account in dynamic LCA study for buildings allows not only to give the range of impact variations but also to understand the dynamic response of the environment following scenarios over time. Table 3-4 shows the scenarios of the French energy production mix collected. We collected data of 4 scenarios from NégaWatt (Association négaWatt, 2017), French Environment & Energy Management Agency (ADEME in French) (ADEME, 2017), and National Alliance for Coordinating Research in Energy (ANCRE in French) (ANCRE, 2013). In terms of the application of the future mix to our case study, we selected ADEME's prospective scenario because of the detailed data accessibility (Section 4.4.5). The future scenario of the French electricity mix is retrieved from ADEME's report shown in Table 3-5.

ADEME's scenarios are developed for two distinct periods: one at the horizon of 2035 and the other at the horizon of 2050. The first is elaborated under the consideration of energy transition without major technological rupture. Energy consumption will be expected to decline by 29% until 2035 and by 45% until 2050 compared to 2010. These results are not far from the objective of the national agreement (LTECV) that imposes 50% of reduction until 2050 compared to 2012. To realize the energy transition imposed in ADEME's scenario, the particular objective in the building sector is related to renovation: 500 000 renovations until 2030 and 750 000 buildings between 2030 and 2050. For the energy production, ADEME proposes three distinct scenarios at the horizons of 2035 and 2050. They are based on the objective of integration of renewables and nuclear options: 1) 2050 - 80% of renewable electricity, 2) 2050 – 90% of important renewable electricity integration and power-to-gat transition, and 3) 2050 – 50% of nuclear energy.

The scenario of négaWatt particularly aims at meeting our goal of *factor 4* objective for the global warming by reaching 100% renewables by 2050. To achieve this goal, their scenario is established based on three main pillars: *sufficiency* (reduction of the overall need by optimizing energy-using services, individually and collectively), *efficiency* (reduction of energy losses through improved technologies), and *renewables* (increase in the part of green energy for supplying the remaining energy demand). This scenario is also constructed by different industrial sectors. As ADEME's scenario, the négaWatt scenario takes also into consideration the importance of the renovation program for the building sector with the objective of renovation of 780 000 residential building and 3.5% of tertiary areas per year by 2050.

Table 3-4: Examples of scenario of French energy production mix

Product name	Dynamic aspects and characteristics	Scenario type	Data / model	Source	Remarks / How to integrate into LCI modelling
ADEME	Production mix of electricity, mix of gas and heat district	Prospective	Change in the vector of electricity production in 2035 and 2050	(ADEME 2017)	• Two scenarios of the mix at the horizon of 2035 and 2050 are proposed
NégaWatt	Production mix of primary energy and electricity	Prospective	Change in the vector of electricity production at every decade between 2010 and 2050	(Association NégaWatt 2017)	• Three scenarios of the mix at every decade from 2020 to 2050 are proposed

Table 3-5: Example of future mix of the French electricity production (ADEME, 2017)

Electricity production	Actual mix		Mix 2050 - 50% of Nuclear power				Mix 2050 - 80% of Renewable energy				Mix 2050 - 90% of Renewable energy			
	2010		2035		2050		2035		2050		2035		2050	
	tep	%	tep	%	tep	%	tep	%	tep	%	tep	%	tep	%
Wind on-shore	0.73	*2%*	4.78	*13%*	4.33	*12%*	5.65	*15%*	7.91	*21%*	6.72	*18%*	11.19	*26%*
Wind off-shore	0	*0%*	0.81	*2%*	0.69	*2%*	2.64	*7%*	5.2	*14%*	3.48	*9%*	7.12	*17%*
Photovoltaic	0.04	*0%*	2.8	*8%*	2.26	*6%*	4.24	*11%*	7.01	*19%*	5.62	*15%*	10.17	*24%*
Hydro power	5.01	*11%*	4.34	*12%*	5.16	*14%*	4.37	*12%*	5.27	*14%*	4.37	*11%*	5.27	*12%*
Marin energy	0.02	*0%*	0.31	*1%*	0.07	*0%*	0.31	*1%*	1.02	*3%*	0.31	*1%*	1.45	*3%*
Wood	0.18	*0%*	1.08	*3%*	2.14	*6%*	1.08	*3%*	2.14	*6%*	1.08	*3%*	2.14	*5%*
Biogas	0	*0%*	0.84	*2%*	1.09	*3%*	0.84	*2%*	1.09	*3%*	0.84	*2%*	1.09	*3%*
Waste incinearation	0.18	*0%*	0.31	*1%*	0.32	*1%*	0.31	*1%*	0.32	*1%*	0.31	*1%*	0.32	*1%*
Geothermal	0	*0%*	0.1	*0%*	0.1	*0%*	0.1	*0%*	0.1	*0%*	0.1	*0%*	0.1	*0%*
Nuclear	31.73	*72%*	18.69	*51%*	18.08	*49%*	14.44	*39%*	4.18	*11%*	12.61	*33%*	2.26	*5%*
Industrial electricity	0.61	*1%*	0.4	*1%*	0	*0%*	0.4	*1%*	0	*0%*	0.4	*1%*	0	*0%*
Blast furnance gas	0.13	*0%*	0.2	*1%*	0.17	*0%*	0.2	*1%*	0.17	*0%*	0.2	*1%*	0.17	*0%*
Natural gas	1.86	*4%*	1.31	*4%*	2.15	*6%*	1.53	*4%*	3	*8%*	1.23	*3%*	1.8	*4%*
Gas - District heating	1.86	*4%*	0.76	*2%*	0	*0%*	0.76	*2%*	0	*0%*	0.76	*2%*	0	*0%*
Other fossil fuels	1.69	*4%*		*0%*		*0%*		*0%*		*0%*		*0%*		*0%*

3.4 Temporal parameters of production and supply chain dynamics

The schedule of a system's production and supply chain can be described by different temporal parameters, for example, the period of products fabrications, transport, stock (waiting time to be delivered, or by the period of use and the time of the end of life. This aspect related to logistics is what makes environmental emissions dynamic over time.

The DyPLCA project developed a database providing the temporal parameters for all background processes aligning with the "cradle to gate" design of systems. The definition of their temporal parameters is shown in Annex I. Meanwhile, temporal parameters of case-specific foreground processes need to be handled in by the LCA users through the DyPLCA web application interface to follow strictly the "cradle to grave" system boundary (CEN, 2012a). We can list some examples of the temporal information of foreground processes to be collected with the corresponding lifecycle phases of EN15978 in the parenthesis:

- Duration of raw material production, its transport to a factory, and fabrications (Phase A1 to A3)
- Duration of material and product transport from a factory to a construction site (Phase A4)
- Time to implement building materials (e.g., putting cement mortar, mixing it with water, drying it, etc.) (Phase A5)
- Time to install construction products (e.g., constructing a building structure, window installation, wooden cladding installation, etc.) (Phase A5)
- Frequency and duration of maintenance, repairing, and replacement (Phase B2 to B5)
- Timing and duration of renovation and demolition (Phase C2 and C4)
- Duration of waste degradation

The choice between different energy equipment alternatives may influence a construction period. For instance, a decision to furbish a gas boiler or a geothermal heat pump system affect the duration of building construction. All these elements should be considered in a construction project. Therefore, the detailed schedule of the construction activities is a key element to ensure effective management and execution of the building construction. Even though our case study (presented in Chapter 4) takes simplified hypotheses regarding the time delay of the schedule for the moment, all of these processes are indeed factors making production and supply chain dynamic. Consequently, the environmental burdens should also have a temporally dynamic behavior.

According to the statistic study on the new construction of housing between 1990 and 2010, the duration of housing construction in metropolitan France varies between 11 and 13 months for the individual houses and of 16 and 23 months for the collective buildings (Commissariat général au développement durable, 2012). The study shows that the duration strongly depends on the economic situation related to the construction market and also on other factors such as typology of a building, surface area, and location.

For the moment, the data collection of this aspect is limited due to the lack of publicly available data. Nevertheless, it will be interesting to investigate how taking into account a more detailed time schedule of a construction affect LCA results with the dynamic metrics. We show in Figure 3-6 an example of the time schedule of the construction of individual housing, established by referring to different sources (“Faire construire sa maison,” 2019; “Les étapes de construction de votre maison !,” 2017).

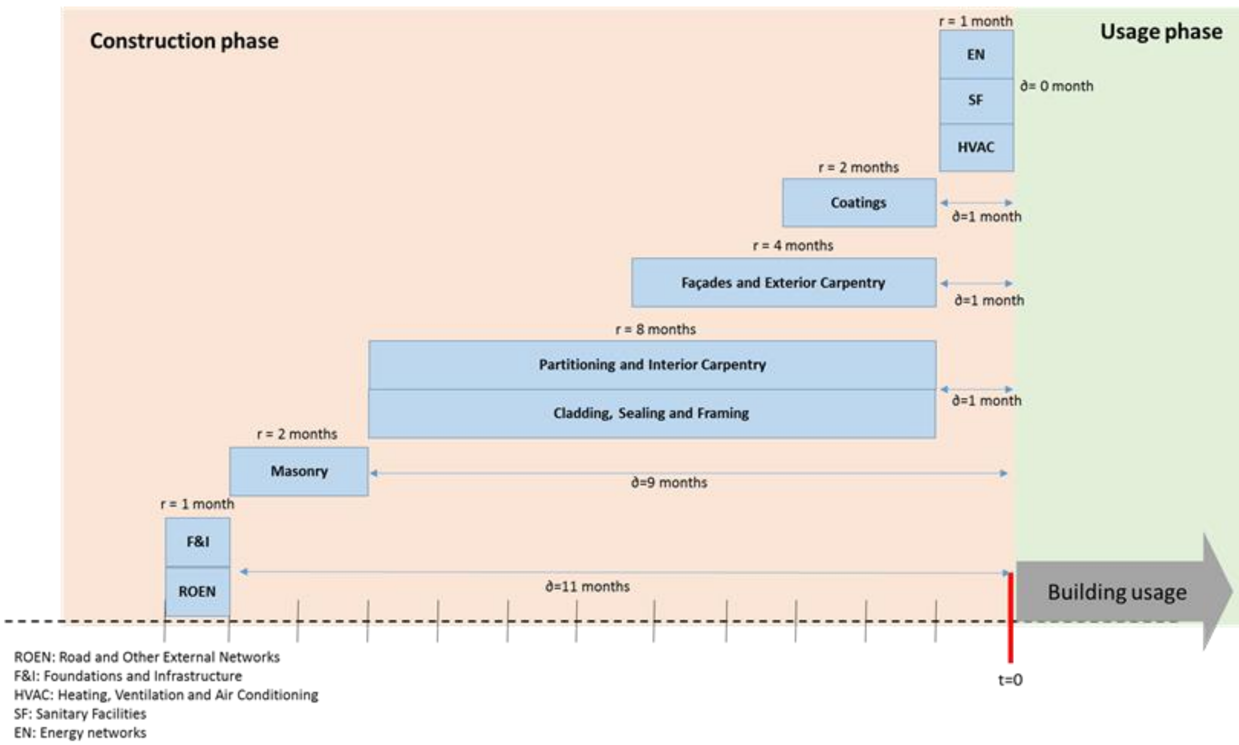


Figure 3-6: Time schedule of the construction of an individual housing

3.5 Conclusion

This chapter introduces our data collection of two distinct types of parameters: "*time-varying building parameters"* that characterize temporal evolutions of building systems and "*temporal parameters"* that characterize the temporality of the production and supply networks. We also describe how to integrate these parameters into dynamic LCI calculations.

In Section 3.2, we provide some important features to understand different natures and temporal characteristics of processes in a building system by classifying time-varying building parameters at different physical levels and system boundaries (fore- and background). It is still necessary to further discuss these classification methods for effective data collection. However, they help the building actors to identify different targets forward in the development of building scenarios and to build dynamic LCI. Keeping these concepts in mind, in Section 3.3, we started constituting building dynamic's database by gathering some time-varying building parameters. Each parameter is investigated based on how it is used to update reference, technological, and environmental flows within dynamic LCI calculations.

This database of time-varying building parameters has just started. It should be further developed during the thesis work; moreover, our literature review was first limited to only certain fields among a huge building system. Our research was first focused on parameters related to technological aspects. However, it is important to extend the parameters research in as many fields of parameters as possible because the establishment of the database is a crucial step towards a complete methodology of dynamic LCA of buildings by totally automating dynamic LCI calculations.

Temporal parameters of a building system are studied in Section 3.4. In order to temporalize LCI of buildings, it is necessary to know how long each lifecycle stage takes. At this moment, our research on time-varying building parameters is limited due to the lack of available public data. Moreover, a deeper analysis of at least three distinct phases (construction, renovation, and demolition) is important to facilitate the implementation of DyPCLA calculation in buildings' studies.

The next chapter aims to effectuate the application of the dynamic LCA methodology for building developed in Section 2.3 and incorporate some collected time-varying building parameters into dynamic LCI model for a case study.

Chapter 4

Climate change pathways with different applications of dynamic LCA: Case study – French low-energy single houses

4.1 Introduction

The previous chapters focused on theoretical development for proceeding to dynamic LCA for buildings. This chapter presents an application of the proposed dynamic LCA methodology for buildings to a test bed case in order to testify its feasibility, to show how dynamic LCA changes results with respect to conventional LCA, and to discuss further improvements of environmental assessment. The usefulness of dynamic LCA in the building sector will be more discussed in 0. Values of temporal parameters, models, LCI calculation tools and database used for implementing a dynamic assessment of this specific case study will be introduced. We selected a newly constructed existing building as a test bed to assess its dynamic climate change pathways throughout the whole lifecycle. Some demonstrations of dynamic LCA have already been done by Shimako during his thesis works and showed the usefulness and applicability of the dynamic LCA. This application to a complete building is the first one performed in the field. Therefore, we developed new features providing some indications for future improvements of this environmental assessment methods and for sustainable developments through the result analysis of this case study, specifically in the building sector. To realize that, dynamic climate change impacts are compared to conventional results that use global warming (kg CO2 eq.), in order to discuss how dynamic LCA changes result interpretations with respect to conventional LCA.

Life cycle stages of buildings are defined in the standard EN15978. Material and energy balances and associated environmental interventions are calculated within boundaries defined for each stage. At the same time, for practical reasons, the conventional LCA of buildings can introduce the notion of "contributor" to simplify the collection, modelling and calculating inventory flows, by segmenting a building lifecycle into four parts. The analysis of LCA results can also be effectuated by contributors. This approach of contributors is introduced for example in ELODIE, a building LCA tool. Figure 4-1 illustrates the link between life cycle stages of buildings and the contributor approach. The short description of each module of life cycle stages and each contributor follows.

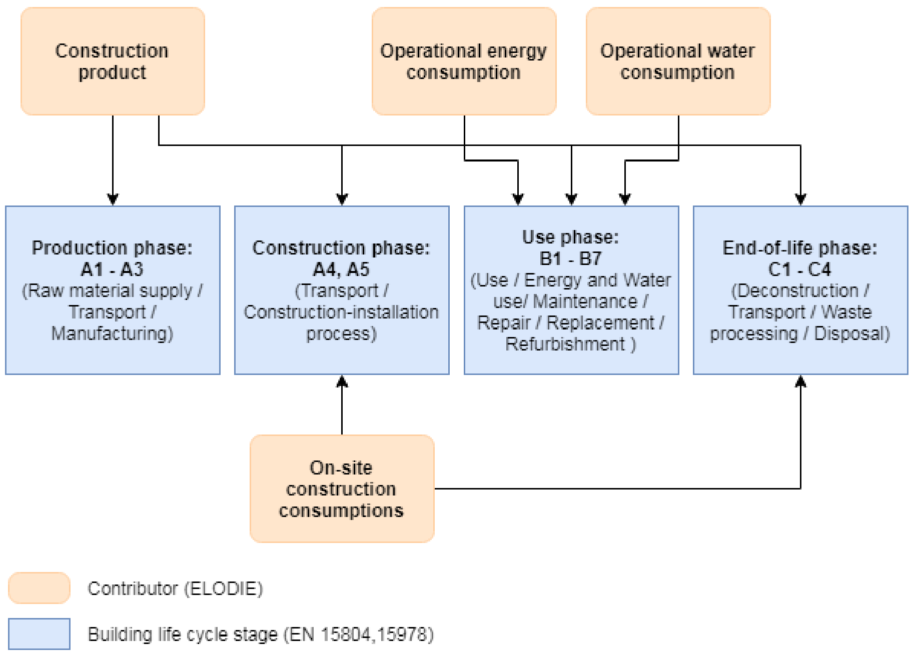


Figure 4-1: Coupling life cycle stages defined by EN15978 standard and "contributor" approach

According to the EN15978 standard, the life cycle stage of the building is broadly divided into four stages with different system boundaries:

- Stage A represents processes during the construction product manufacturing (A1 to A3) and building construction phase (A4 and A5). A1 to A3 cover, within the boundary of the production stages, "cradle to gate" processes for the materials and services that are necessary as preliminary steps of the building construction. A4 and A5 cover the processes of transport of materials and construction products provided by the factory in precedent stages and the process of building construction and product installation on the construction site;
- Stage B covers the processes taking place during the operational use phase of a building. The module includes not only the operational energy and water use but also activities such as maintenance, repair, replacement and refurbishment allowing to ensure a required technical performance level of the building. Moreover, processes associated with these activities such as removal and transport of materials are considered.

- Stage C includes processes from building demolition to final disposal of materials. The scenario of the waste processing is to be defined if materials are recycled, reused, recovered or completely disposed of as a landfill scenario after their lifetime.
- Stage D, which is not included in the above figure, quantifies benefits of material and energy balances through reuse, recycling, and energy recovery issued from an existing system. Therefore, the quantification of inventory flows within the module D goes beyond the system boundary of investigated buildings.

As can be seen in the figure, there are four contributors designed in the current LCA practice for buildings:

- "Construction products" contributor takes into account all components of the building through its life cycle. Material and energy balances and associated environmental interventions are obtained from EPDs.
- "Operational energy consumption" contributor covers all the uses of energy during the building use. The embodied energy, which is the energy necessary for equipment and construction materials production, is accounted for in "Construction products" contributor.
- "Operational water consumption" contributor covers all the uses of water during the building use. The water consumption during material and product manufacturing or on the construction site is allocated to the contributors "Construction products" or "On-site construction consumption."
- "On-site construction consumption" contributor accounts for the consumptions of energy, water, other materials, the production of waste water, and the evacuation and treatment of soil during the construction.

Figure 4-2 shows the framework of this chapter dedicated to a test bed building. A preliminary conventional LCA was performed using LCA tools for the building sector, i.e., ELODIE software and INIES – EPD data base. This first assessment gave us a trend of climate change impact based on GWP metric with a focus on contributors and helped at defining a proper inventory of the studied building. Then conventional LCA was performed with SimaPro software using ecoinvent database completed with inventory elements from the first assessment. The same system model defined in SimaPro, with the same inventory data, was then used for DLCA. The obtained conventional impact results and temporal impact results were then discussed and compared.

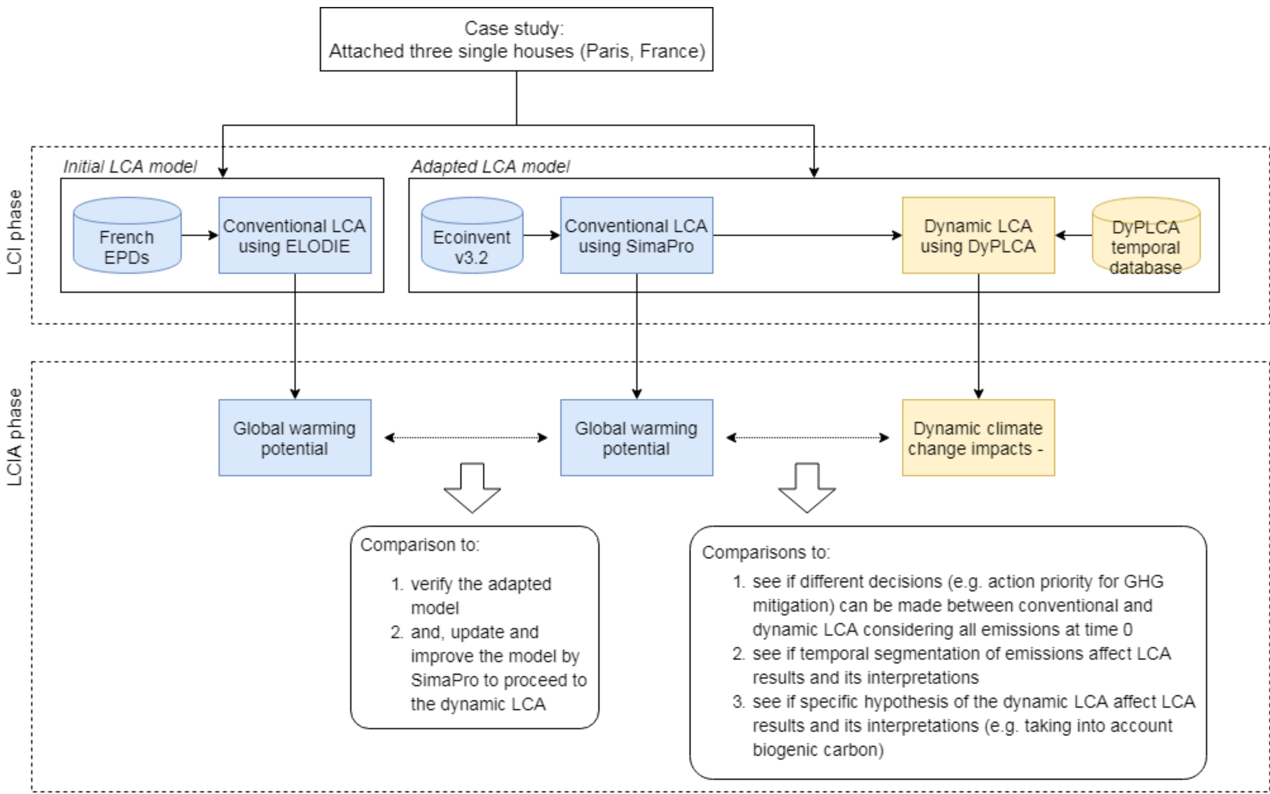


Figure 4-2: Description of different LCA models applied to the case study

In our case study, ELODIE was used for the preliminary LCA study of the test bed. ELODIE is a simplified LCA tool thanks to the usage of EPDs in order to model LCI of buildings and calculate impacts at different scales (construction products, contributor, and building). The software is directly connected to INIES database gathering French EPDs. Therefore, modelling can be effectuated at the construction product scale and in the French context (e.g., the use of the French mix of energy production), contrary to other generic LCA software usually based on an LCI modelling at the process (activity) level.

Once the preliminary conventional LCA study was achieved, we proceeded to dynamic LCA of the same building. However, while EPDs and modelling with ELODIE provide only information about environmental impact categories (detailed LCI is not provided by the software), most public EPDs do not show any information on environmental flows. More precisely, EPDs indeed disposed of detailed LCI but not digitalized in publicly accessible INIES database (Lasvaux, 2012). Therefore, we needed to remodel LCI of the same building with a complete inventory data set. To overcome this problem, we selected ecoinvent database for the following two reasons. At first, ecoinvent contains a wide variety of inventory data with more than 15,000 processes. At second, DyPLCA project has developed the database of temporal parameters of background processes based on ecoinvent. SimaPro LCA tool was used to model the building with ecoinvent database as it is widely used by LCA practitioners. Finally, SimaPro LCI model was used as an input of DyPLCA web application to build dynamic LCI.

Conventional LCA results using SimaPro and ecoinvent were compared to the preliminary conventional LCA result to ensure that there are not significant differences between them and to improve SimaPro LCA model when important differences are observed. Once SimaPro LCA results were analyzed, DyPLCA model was established. Then, dynamic LCA results are compared to conventional SimaPro LCA for the following reasons:

- See if temporal segmentation of emissions affect LCA results and its interpretations
- See if the specific hypothesis of the dynamic LCA affect LCA results and its interpretations (e.g., taking into account biogenic carbon)
- See if different decisions can be made between conventional and dynamic LCA (e.g., priority action for GHG mitigation).

Environmental assessments are performed for each contributor of buildings (construction products, operational energy consumption, operational water consumption, and on-site consumptions) for climate change impact indicators. Then, the contributions of each construction product family were analyzed. This contribution analysis allows also understanding greenhouse gases behavior over time in a more realistic manner than conventional LCA cannot evaluate. Finally, climate change pathways over time are evaluated with prospective scenarios of the building system.

Section 4.2 will describe general information of the used building model for the case study and show a preliminary impact analysis with conventional LCA. Section 4.3 will briefly introduce models, LCI databases, calculation tools used for the implementation of dynamic LCA of this case study. The test bed's building will be characterized by temporal parameters for dynamic process modelling (time scheduling of process flow) as we have seen in Section 3.4. Section 4.4 will give models and data to provide LCI with the integration of building specific temporal evolutions. Finally, Section 4.5 will be dedicated to analyzing dynamic results with respect to conventional results in order to improve our understanding of the environmental impacts of buildings.

4.2 Preliminary LCA of the test bed building using ELODIE software

The buildings selected as a test bed are three attached single houses based on wood, located in the Paris region, in France. These houses are issued from the "Observatory" project, an experimental platform for environmental assessment preparing a new French energy and environmental regulation "E+C-" ("French Ministry of the environment, ministère de la transition ecologique et solidaire" 2016).

The function of houses (construction, utilization, end of life) is considered to be assumed for 50 years (2015 to 2065). The total net floor area of three houses is 414 m², each house is two-storied. The system boundary for the LCA study includes from primary material productions to the end of life, according to the standard EN15978 (CEN, 2012a).

Data collection and assumption was done within “cradle-to-gate” boundary complying with the standard EN15978 with respect to the functional unit of the case study, i.e., three attached single houses for 50 years.

The collected data in the EPDs represent existing buildings recently constructed. The available information includes at least the name of building components, their quantity and lifetime, which can be used in both static and dynamic LCA modeling (introduced in Section 2.3). The total number of EPD used for the studied houses is 63. The initial model of the houses has been realized with the aid of ELODIE, LCA software specific to the construction sector linked to INIES database gathering EPDs. Some construction products having a lifetime inferior to 50 years (information retrieved from EPDs) are replaced by new ones.

The distance of transportation of construction products from factories to the construction site is taken from EPDs. However, some products of the original building LCI model does not possess their EPDs and are referred to generic product LCI models provided by CSTB with their hypothesis for transport distance (MEEM and MLHD, 2016). When the transport distance is not given, it is systematically set to 100 km (Lasvaux, 2012). At the end of life, energy consumption to demolish and transport of building materials from the building site to the waste disposal site were accounted for, and different waste treatment processes (landfill, incineration, and recycling) are considered for different types of waste materials on the basis of EPDs.

All the energy demand is satisfied by electricity. Total energy consumption for the five posts of energy equipment, i.e., heating and cooling system, domestic hot water (DHW), ventilation system, and lightning, estimated by the dynamic energy simulation tool COMETH (Haas and Corrales 2014), is 36.9 kWh/m²/year for the first year of the building use. Besides, the annual consumption of domestic appliances for this building is set to be 20 kWh/m²/year according to expert opinion (Sidler, 2009). Table 4-1 summarizes the general information of the studied houses.

Table 4-1: General information of the studied buildings on the basis of the ELODIE model

Building model	**Three attached single houses**
Type of building	Residential, new construction
Type of structure	Timber post and beam
Type of insulation system	Timber frame
Lifetime of the building [year]	50
Net floor area [m²]	414 (for three houses)
Type of energy	Electricity for the heating/cooling system, DHW, ventilation, light
Energy equipment	Electric convector (heating), Heat pump (DHW), Mechanical ventilation system
Energy consumption [kWh/m²/year]	36.9 (for three houses)
Number of inhabitants	15 for three families

Environmental impacts were calculated following the LCIA methods implemented in ELODIE. Required impact indicators to be evaluated are those defined in EN15804 for construction products and in EN15978 for the building (CEN, 2012a). Nowadays, 26 indicators are calculated in 4 categories: environmental impacts, natural resource depletions, eliminated waste and valorized waste (MTES and MCT, 2017).

Table 4-2 shows the environmental impacts of this building through four contributors calculated with ELODIE in the framework of the “Observatory” project in order to analyze the contribution of major intermediary flows: construction materials used overall in the life cycle (“construction products”), energy consumption in use phase (“operational energy consumption”), water consumption in the use stage (“operational water consumption”), and material, energy, water consumptions and waste from construction operations (“on-site construction consumption”).

The direct emissions from the construction materials in the building’s use stage are not accounted for, because of the lack of our understandings of biological, physical, and chemical phenomena involved in material evolution.

“Construction products” (fabrication of the construction products used over the whole life cycle) seems to be the most impacting for almost all calculated indicators (figures in italic in Table 4-2). In the following, we focus on climate change impact. This contributor (construction products) contributes with 2.23E+05 kg CO_2 eq, which takes 67% of the total. Figure 4-3 shows the relative contribution of the four main contributors defined above, to global warming indicator. "Construction products" is followed by "Energy consumption" and then by "On-site construction consumption."

Table 4-2: Environmental impacts of the test bed building by 4 contributors (the most important phase for each impact category is shown in italic)

Environmental impacts	**Construction products**	**Operational energy consumption**	**On-site construction**	**Operational water consumption**	**Total**
Global warming (kg CO_2 eq.)	*2.23E+05*	8.78E+04	2.23E+04	1.73E+02	3.34E+05
Ozone depletion (kg CFC-11 eq.)	*1.23E-02*	8.43E-02	2.14E-02	5.83E-05	1.18E-01
Acidification for soil and water (kg SO_2 eq.)	*7.93E+02*	4.12E+02	1.29E+02	9.85E-01	1.33E+03
Eutrophication (kg $(PO_4)_3$- eq.)	*1.44E+02*	5.65E+01	2.40E+01	2.45E-01	2.25E+02
Photochemical ozone formation (kg C_2H_4 eq.)	*7.30E+01*	1.95E+01	1.08E+01	1.33E-01	1.03E+02
Depletion of abiotic resources - elements (kg Sb eq.)	*3.97E+02*	5.44E-01	1.26E+00	9.26E-04	3.98E+02
Depletion of abiotic resources – fossil fuels (MJ)	*1.32E+06*	1.38E+06	4.01E+05	2.53E+03	3.10E+06
Air pollution (m^3 of air)	*1.97E+07*	4.36E+07	1.11E+07	4.18E+04	7.19E+07
Water pollution (m^3 of water)	*1.58E+06*	2.42E+04	1.26E+04	1.65E+03	1.62E+06

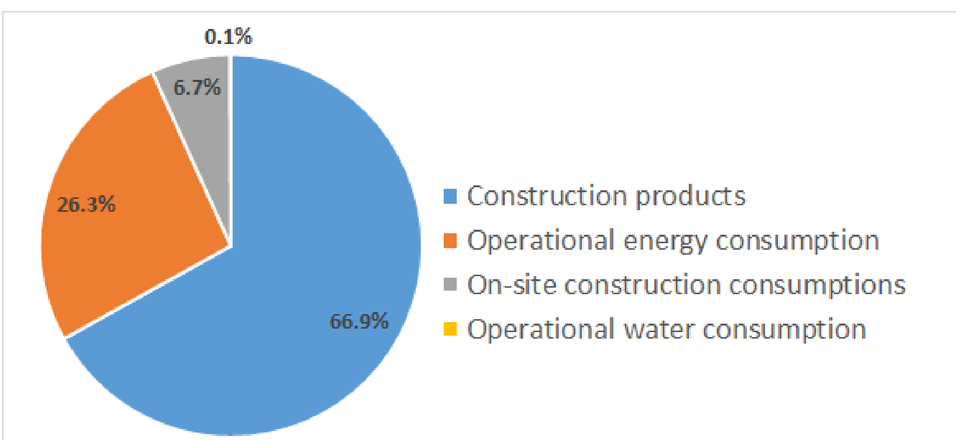


Figure 4-3: Global warming (result of conventional LCA) impact share between the building contributors

According to Figure 4-3, analyzing the contribution to global warming, the mitigation efforts for GHG reduction in this testbed building should be oriented towards "construction products" contributor. Furthermore, altering construction products to improve their carbon footprint and integrating renewable resources into energy production would be solutions for long-term GHG emission mitigation. This fact meets the necessity of performing an impact analysis of future building technologies.

4.3 Dynamic LCI and LCIA

4.3.1 General methodology of DLCA

In Section 2.3, we developed the general methodology based on which the present case study is performed to testify the feasibility of the methodology. The steps of methodology application are schematically described in Figure 4-4 and briefly recalled in the following.

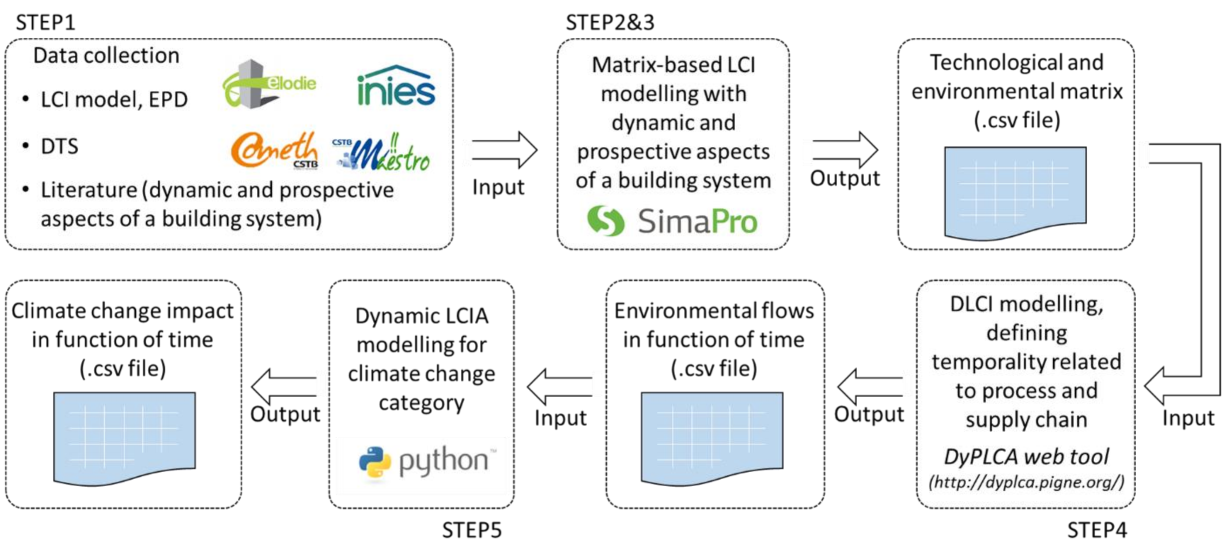


Figure 4-4: General framework of the application of dynamic LCA to the case study

STEP1 (Data calculation and collection). The collection of building data for LCI and of the dynamic aspects and prospective scenarios, as presented in the previous section, is performed on the base of EPDs, literature review, expert opinion. This step includes the Dynamic Thermal Simulation (DTS) providing annual energy consumption that is then used as input of LCA modeling. COMETH is used as DTS software in this case study.

STEP2 (Static model of the life cycle system). Energy and material balances are calculated at the process level throughout a whole system of building's life cycle, and the matrix of technological and environmental flows of the system is generated. In this conventional LCI model, inventory flows that occur at different life cycle stages should be identified as flows associated with different activities.

STEP 3 (Dynamic model of building systems). Building's dynamic behaviors and its prospective scenarios are integrated into the LCI model regarding data collected for a specific goal and scope of the investigated case study. Energy and material balances should be uploaded here concerning the created scenarios and keeping a matrix-based output format. Temporal characteristics of the building system rely broadly on, following Section 3.2.2, three categories: 1) building intrinsic system, 2) inhabitant behavior and 3) background system of the building. The temporal aspects are incorporated as temporally specified processes into the LCI model.

STEP 4 (Dynamic model of the supply chain). The dynamic modeling of LCI is performed, in which technological and environmental flows are expressed in function of time through the building's life cycle. The matrix-based conventional LCI is imported into the DyPLCA web application (http://dyplca.pigne.org/) to calculate the temporal distribution of emissions through the life cycle of buildings. The web application allows to define a temporality of the whole system (foreground and background system) and to calculate technological and environmental flows in function of time with the aid of a specific temporal database. The database gives temporal information related to the network of the supply chain such as a functioning period of processes, delivery and stock period of products supply, a lifetime of products. For processes in the foreground system, i.e., processes defined with case-specific data (e.g., replacement of windows at year 30), the temporal information is retrieved from the literature review, databases or expert opinions.

STEP 5 (Dynamic LCIA calculation). The result of dynamic LCI computation is used as input to calculate climate change impact in function of time: the radiative forcing [W/m²] and the increase in global mean temperature [K]. We use the computation model of these two indicators previously developed by Shimako et al. (2016).

4.3.2 Dynamic LCI modeling

4.3.2.1 Data collection for LCI modeling

To generate a reliable DLCI model of the case study, we combined a variety of tools, software, databases, and methods. As explained above, DLCI is based first of all on the static LCI. So data collected (inventory) will serve for conventional LCA and DLCA in the following sections. Moreover, different data sources presented in Table 4-3 were incorporated to model the inventory, perform dynamic energy simulation, and to establish the DLCI model in our case study.

Table 4-3: Data sources used in the case study

<table>
<tr><th>Data source</th><th>Data retrieved</th><th>How to use data?</th></tr>
<tr><td>“Observatory” project data</td><td>Building general description
Dynamic energy simulation model already developed by the expert</td><td>- Used to calculate material and energy consumptions of the building life cycle.
- Dynamic energy simulation is realized by COMETH</td></tr>
<tr><td>ELODIE model</td><td>Name, quantity and lifetime of construction products and materials</td><td rowspan="3">- These data are involved in setting reference flows which are used for conventional LCI modelling with SimaPro
- Other information (e.g., lifetime of products) are used in DLCI modelling</td></tr>
<tr><td>FDES</td><td>Name and quantity of processes of technological flows</td></tr>
<tr><td>Ecoinvent v3.2</td><td>Inventory flows (technological and elementary)</td></tr>
</table>

The LCA software SimaPro® 8.5.0.0 as well as the ecoinvent 3.2 database were used for the modeling of LCI (STEP2). The geographical information of FR (France) for inventories is privileged when data is available, whereas RER (Rest of Europe Region excluding Switzerland data) or RoW (Rest Of the World excluding Switzerland data) was used as an alternative solution for others. Also, “Default allocation method” for process modeling of ecoinvent database was chosen.

We used MAESTRO platform, which is the core interface for Dynamic Thermal Simulation of COMETH, and the model developed was then used as an input into COMETH to simulate annual energy consumption. These tools allow for an easy configuration of dynamic parameters, e.g. building’s physical characteristics, scenarios of occupation, climate condition to generate annual energy consumption for the following years.

For the sake of simplicity of LCI modeling, some construction products are excluded from the model, particularly when: (i) global warming score of a product is very low (the threshold of cut is set to 1% of representativeness of global warming score); (ii) inventory data is completely lacking, or (iii) the mass is not representing much among the total mass of houses (the threshold of cut is set to 1% of representativeness of the total mass of the testbed building).

The total mass of the building was first calculated based on the information retrieved from ELODIE and corresponding EPDs. Some EPDs cannot be anymore found because of the expiration of data validity period.

In that case, we estimated the missing value by using the corresponding ecoinvent data. The simplified LCI is obtained by:

1. Construction products the contribution is smaller than 1% of the whole house in terms of global warming score are eliminated.
2. Packages for all products are excluded as they represent only a few contributions to climate change and mass (Lasvaux, 2012).
3. All insulation materials are included even though some of them do not respect the first criteria of model simplification.
4. In case that eliminated products are considerably heavy, they are even so included in the LCI model.

After the simplification, the model represents still 98% in terms of the mass flows with respect to the original ELODIE model. Finally, the case study model includes 48 construction products among the 63 initially identified, and the representativeness in terms of the global warming potential (kg CO_2 eq.) is 97% concerning the ELODIE model.

The original ELODIE model, based on which we realized the modeling of the houses using SimaPro and ecoinvent datasets, uses for some of the inventories the generic construction product data that give no explicit details of the background inventory. These generic data are supplied by CSTB when there is no EPD for a particular product or when the information regarding product characteristics is significantly lacking. Thus, a part of our building model in SimaPro used as reference these generic data.

4.3.2.2 Dynamic LCI modelling using DyPLCA tool

As noted in Annex I, DLCI modelling needs a certain number of temporal parameters involved in the two distinct mathematical models: 1) “process” model defining the main temporal characteristics of the processes in the system process network, and 2) “supply” model defining the relations between processes in the supply chain. Based on ecoinvent dataset, these temporal parameters are collected into a dedicated database to which DyPLCA web application has access. These ecoinvent processes for which temporal parameters are predefined in the DyPLCA tool are processes of the “background system.” However, users can manually modify these temporal parameters if needed. Meanwhile, users are required to define themselves temporal parameters of created processes in the “foreground system” via DyPLCA web application. Table 4-4 synthesizes the scenarios of the test bed building giving a temporality of each stage of the lifecycle.

Table 4-4: Description of the temporality of the main activities involved in the building life cycle

Module EN15978	**Occurrence time, years**	**Process/activity**	**Description / indication**
A1 – A3	t < -1	Product fabrication	Product fabrication processing related to the construction activity
A1 – A3	t = [0,50]	Product fabrication	Product fabrication processing related to the maintenance and replacement activities
A4 – A5	t = [-1, 0]	Construction	Construction period is 1 year, energy and water consumptions are considered
B1	t = [0, 50]	Building use	The reference time 0 is the start time of building use
B2	t ∈ [0, 50]	Maintenance	Wall paintings
B4	t ∈ [0, 50]	Replacement	Replacement of windows, doors, HVAC systems
B6	t = [0, 50]	Energy use	End-user’s energy consumption takes place over the lifetime of the building
B7	t = [0, 50]	Water use	End-user’s water consumption takes place over the lifetime of the building
C1 – C4	t ∈ [0, 50]	Waste treatment	Products replaced by new ones are treated with end-of-life scenarios
	t = [50, 51]	Waste treatment	The building is treated with end-of-life scenarios

We briefly recall here the main principles of the DyPLCA model and application method. A dynamic LCA modelling starts by a conventional matrix-based LCI obtained with an LCA software (in our case Simapro). Technology and environmental matrixes are then imported into DyPLCA tool which transforms them in a graph structure representing supply chains. Then, a search algorithm runs through the graph to trace the sequenced time of processes. Each node (process) of a graph has its temporality for the unit production of a product (r value) and the representative period during which functions provided by the node are effective (T value), which is, in another word, the lifetime of the supporting infrastructure. As r value is considered as a period of production, technological flow (named function alpha α) and associated environmental emissions (named function beta β) are defined for r. We can also define delays or specific periods on the time scale at which processes are happening thanks to a dedicated temporal parameter (δ). Setting supply frequency (τ value) enables us to calculate in how many batches the supply of a product is performed (periodical or continuous supply). Temporal granulometry of these parameters can be as thin as possible (e.g., even inferior to a second) up to years.

In DyPLCA tool, the time scale is referred concerning the process which ensures the function of the studied system, for which the starting time represents t=0 (the process lifetime of working time is T years).

However, time zero can be placed everywhere on the life cycle timespan, by a simple translation of the time scale origin. In our case study, time zero is placed at the beginning of the use stage of the building, i.e., construction occurs at t<0, use stage occurs for t>=0.

Nonetheless, only these definitions are not sufficient for users to understand how the dynamic method can be specifically applied to building case, because of the complexity of a building system and long time scale consideration.

Process model

In this case study, a new process named *"Building"* was created, which ensures the function (and the functional unit) of the studied system. Its lifetime is T = 50 years. The r value of the "building" process does not physically represent the production of technological and associated environmental flows. Here, setting r = T = 50 signifies that the studied system has inputs (such as material, energy, and water) to keep the building being under operation. Also, direct emissions from the building itself can be defined using their own r value. For instance, material degradations occurring over the lifetime of the building would have direct environmental burdens, and the r value is used as a period of environmental flow existence.

In order to place on the lifetime scale of different types of activities, several new processes were created. These new processes do not have the same general temporal characteristics as those attributed to the products and activities in DyPLCA database. They are rather fictive processes, fulfilling the role of the cursor on the timeline for placing real activities at the desired point in time.

Processes that mention *"(construction product name) | Year …"* (e.g., PVC Windows | Year 30) have a purpose of placing some production processes of construction products at a given year. They have no environmental interventions. Processes placed at year 0 and 50 represent activities for the building construction and for the building's end of life, respectively.

Moreover, processes placed at the year between 0 and 50 represent activities such as maintenance, replacement, and refurbishment. Our case study considers each of these activities has a representative period of 1 year, thus T = r = 1. The production function alpha is thus considered as a constant and unitary value divided by T (α=1/T).

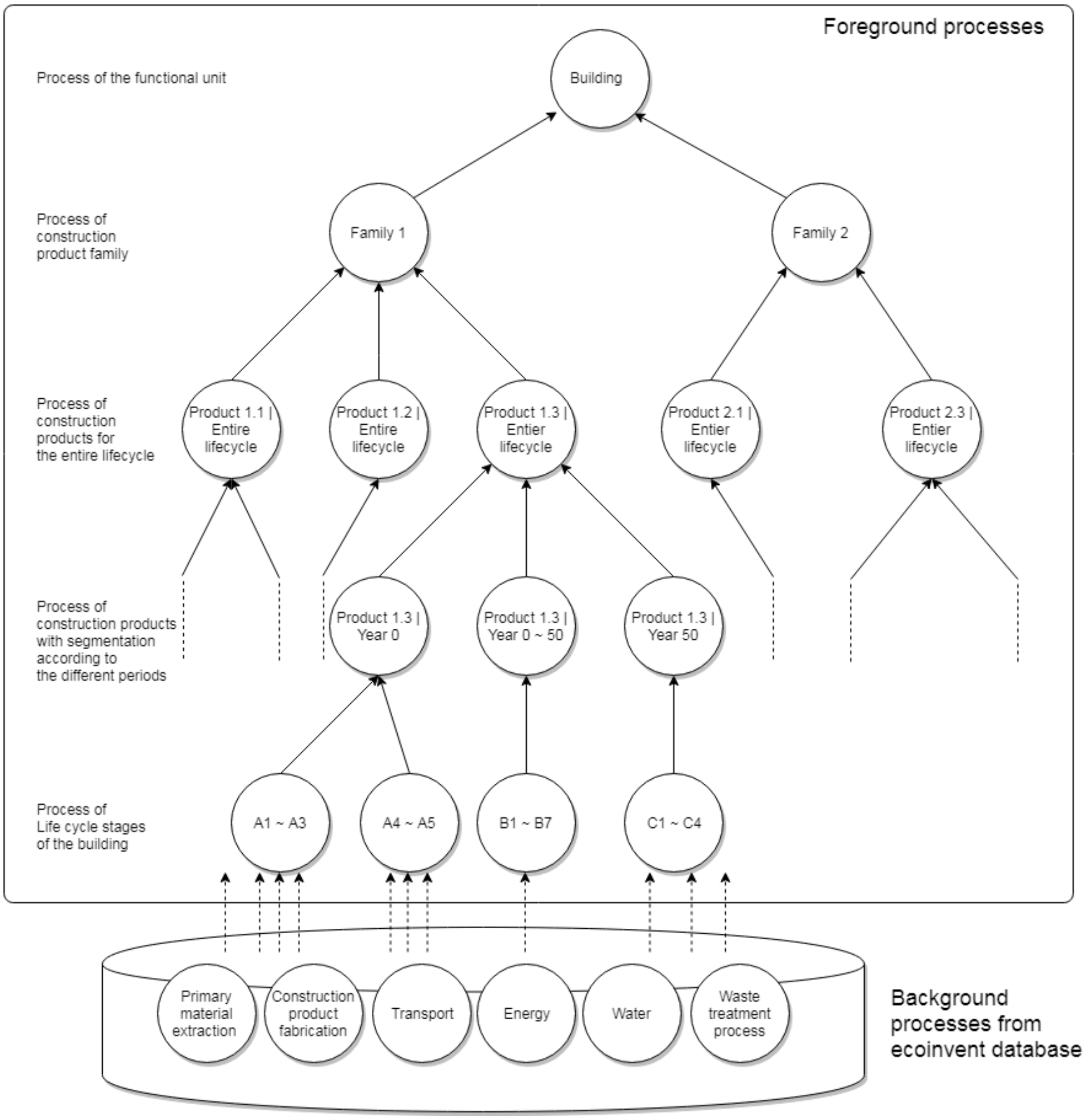
Processes that mention *“(construction product name) | Entire lifecycle”* (e.g., PVC Windows | Entire lifecycle) have the role of putting together all activities related to a product over the whole lifecycle of the building. There are no environmental interventions.

Processes that mention *“(construction product family name)”* (e.g., Foundation & Infrastructure) have the role of gathering processes of different construction products in the same family, together into one process. Thus, they do not represent a physical meaning, and no emissions are considered.

Structuring construction processes into families (construction products having the same functionalities) follows the categorization by the new French energy and environmental regulation “E+C-,” allowing for a comprehensive LCI modelling. There are 13 family groups all in all, and the case study considers the first 10 families (Table 4-5).

Table 4-5: Family groups of construction products according to E+C- reference

1	Highways and miscellaneous external works (H&MEW)
2	Foundations and Infrastructure (F&I)
3	Superstructure and Masonry (S&M)
4	Roofing, Tightness, Framework, Flashing (RTFF)
5	Partitioning, lining, suspended ceiling, interior carpentry (P&IC)
6	Façades and exterior carpentry (F&EC)
7	Coverings
8	Heating, Ventilation, Air Conditioning (HVAC)
9	Sanitary facilities (SF)
10	Energy networks (EN)
11	Communication networks
12	Lifting equipment and other internal transport equipment
13	Equipment for local energy production


Foreground processes
Process of the functional unit
Building
Process of construction product family
Family 1
Family 2
Process of construction products for the entire lifecycle
Product 1.1 | Entire lifecycle
Product 1.2 | Entire lifecycle
Product 1.3 | Entier lifecycle
Product 2.1 | Entier lifecycle
Product 2.3 | Entier lifecycle
Process of construction products with segmentation according to the different periods
Product 1.3 | Year 0
Product 1.3 | Year 0 ~ 50
Product 1.3 | Year 50
Process of Life cycle stages of the building
A1 ~ A3
A4 ~ A5
B1 ~ B7
C1 ~ C4
Primary material extraction
Construction product fabrication
Transport
Energy
Water
Waste treatment process
Background processes from ecoinvent database

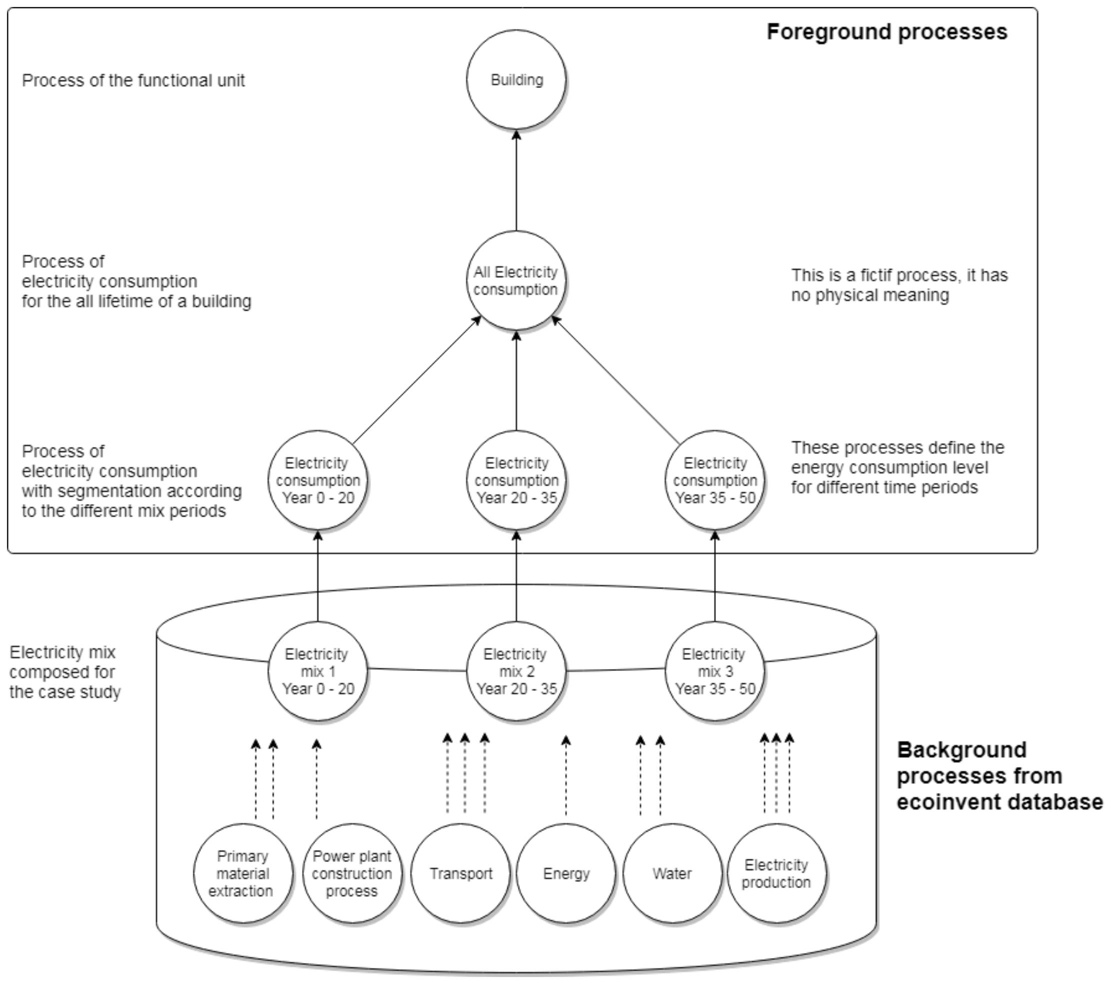


Figure 4-5: DLCI modelling structure with DyPLCA tool: top – construction products for entire lifecycles; bottom – electricity consumption in building's use stage

Regarding electricity consumption by end-user, the modelling was conducted separately. For the baseline energy consumption that is based on the current production mix process of ecoinvent dataset ("electricity, low voltage {FR}| market for"), annual consumption estimated thanks to DES by COMETH was replicated 50 times in order to build the dynamic LCI over the building lifetime. The future electricity mixes were modeled (more details are given in Section 4.4.4) as processes of ecoinvent, and these new processes were applied instead of the current mix. Figure 4-5 shows the principle of connecting the foreground processes for construction products in the building life cycle and the electricity consumption in building's use stage.

Supply model

Concerning supply model, the "delay" parameter δ depends on the relationship between two processes. The temporal database implemented in DyPLCA tool contains by default values for the ecoinvent processes. Thus, we need to define the temporal parameters of our foreground processes. Considering the relation between a producer process and a consumer (the consumer uses the product supplied by the producer), when only one supply is needed (for example the door is delivered only one time, at a given t, e.g. t=0), the DyPLCA model requires that τ = Tc, with Tc the representative period of the consumer process.

Our foreground processes called *"(construction product name) | Entire lifecycle"* and *"(construction product family name)"* introduced just above do not have a physical meaning. Therefore, we can define their time schedule as $\delta = 0$ because they can be considered to be produced at the same time as the "Building" process, or we can consider that there is no delay between the end of a producer process and the beginning of a consumer process when $\delta = 0$. However, as for processes called *"(construction product name) | Year Y,"* we need to set δ= -Y+r in order to introduce time delay with r for a production period. For example, considering a replacement of certain construction product taking one year and the replacement occurs at 30 years, the process of "Construction product | Year 30" has δ= -31. Here, the negative value is used because in the calculation program the parameter has positive value when we want to place a producer process earlier with respect to a consumer process. It is important to note that, for the processes named "year 0", they occur in the year -1, i.e., during the year before the inhabitants start to live in the house. Therefore, the year for these processes is -1. Thus their delay in relation to the building timeline is zero.

Figure 4-6 presents the production and supply of only two processes where the process 1 is the functional unit and defines the start time t_0. As we can see, the values of T, r, and δ make the process 2 be placed at a moment when the process is needed. In the same manner, we can define the temporality of all processes both in the fore- and background thanks to DyPLCA tool.

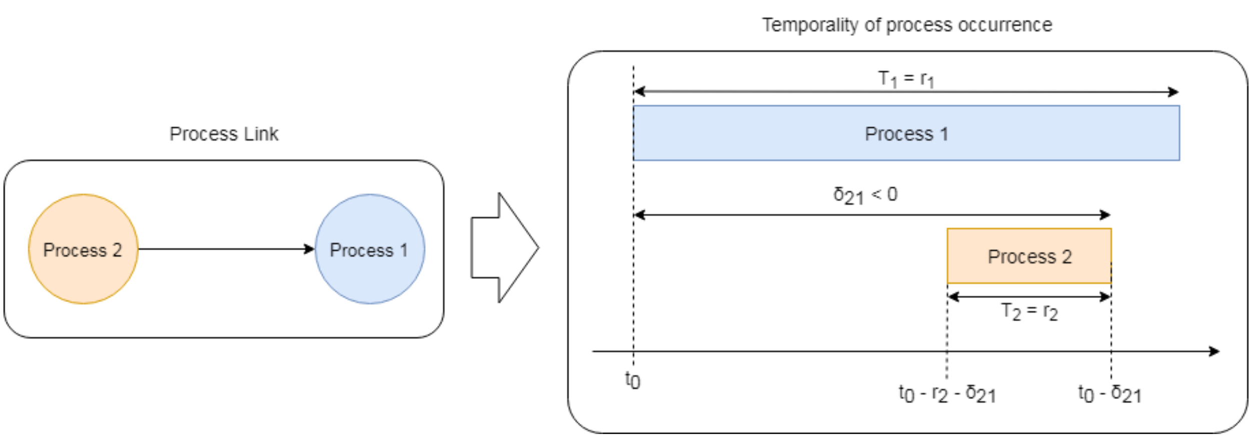


Figure 4-6: A simple example of supply chain modelling for 2 processes.

4.3.3 Conventional and dynamic approaches for climate change impact

4.3.3.1 Metrics of climate change impact assessment

Global warming potential (kg CO_2 eq.) of the IPCC model (IPCC, 2013) is used in conventional LCA applied to the case study. In contrast, as proposed in Section 2.3.4, dynamic climate change impacts are evaluated in terms of instantaneous radiative forcing (W/m²), cumulative radiative forcing (W/m².year), and global mean temperature change (K). The dynamic and linear system modelling of climate change impacts considers the atmospheric distribution of GHGs over time and their effects on radiative forcing and mean temperature change. The number of concerned chemical substances accounts for 37 (e.g., CO_2, CH_4, refrigerants) and combining them with environmental compartments and sub-compartment (e.g., high population, low population) according to ecoinvent LCI models, makes up 81 types of GHGs in total. The whole list of considered GHGs is given in Annex III. For CO_2, CH_4, and CO, these emission flows are taken from different sources: biogenic, fossil fuels, and land transformation. Furthermore, the dynamic model considers also methane oxidation as presented in (Shimako, 2017).

4.3.3.2 Consideration of biogenic CO_2

Different approaches to account for different types of CO_2 are investigated in recent studies (Wiloso et al., 2016). For global warming impact calculation, we accounted for the absorption and emission of the carbon related to biomass products, that we call here “biogenic carbon.” Some authors mentioned that the forest management (cyclic period of trees growth, occurrence time of forestation or afforestation) is one of the factors determining the CO_2 balance in the atmosphere due to biogenic carbon flows (Helin et al., 2013; Fouquet et al., 2015). According to the process-related temporal database developed as part of the project DyPLCA (Tiruta-Barna et al., 2016), a tree growth period during which CO_2 is absorbed depends on tree species with a range from several years (e.g., eucalyptus) to more than 100 years (e.g., oak). Following the supply chain of our specific case study, trees are considered to have been planted and have grown to be ready for the fabrication of construction products. Therefore, first emissions related to tree plant processes and CO_2 uptake should be placed more than 100 years back from the construction.

We also accounted for the carbonation, which is a process of the CO_2 uptake into the cement products through a life cycle of a building (usage and waste treatment processes). The amount of carbonation is determined with the physical properties of cement based products (Pommer and Pade, 2005). We estimated the amount of CO_2 absorbed by each cement products based on values retrieved from each EPD.

Accounting for these two carbon flows and their temporality is necessary for a more consistent evaluation of climate change impact.

4.4 Prospective scenarios

In this chapter, the influence of time variable characteristics of the building system on climate change impact is investigated. The types of temporal parameters considered in this work are: 1) degradation of material and energy system functioning, 2) Technological progress related to the building materials, 3) evolution of the typology of family, and 4) future mix of electricity production. Hereafter, time variable parameters, mathematical models, and long-term scenarios of these four dynamic aspects are described, and their influence on inventory and impact results is evaluated.

4.4.1 Degradation of materials and energy system functioning

Insulation materials used for walls, floors, and ceiling are known for their sensitivity to climate conditions, particularity to the humidity. The thermal performance level is thus degraded over time during the use phase of a building (Section 3.3.1). Three types of insulation materials (rock wool, glass wool, polyurethane) are used in the houses, differentiating their usage type, e.g., exterior wall, upper floor, etc. Temporal profile of the heat transfer coefficient was estimated for each insulation type (Choi et al., 2018; Stazi et al., 2014). The estimation was realized at the yearly time step during their service lifespan to calculate the annual demand for heating and DHW systems for the following years. The building heat loads are also inferred by performance levels of energy equipment at the end-user level. We assumed the degradation of energy efficiency for two principal energy consumption posts: heating by the electric convector and DHW by the heat pump system. We applied the pessimist scenarios of degradation from a previous study (Hendron and Paper, 2006) assuming that global energy efficiency of electric convector and coefficient of performance (COP) of the heat pump are degraded by 1% and 3%, respectively, with respect to a preceding year. Figure 4-7 shows a simplified graphical description of models of the temporal evolution of their technical performances over the building's lifecycle with system replacement every decade. This assumption is introduced into the dynamic thermal calculation model to estimate energy consumption for the following years.

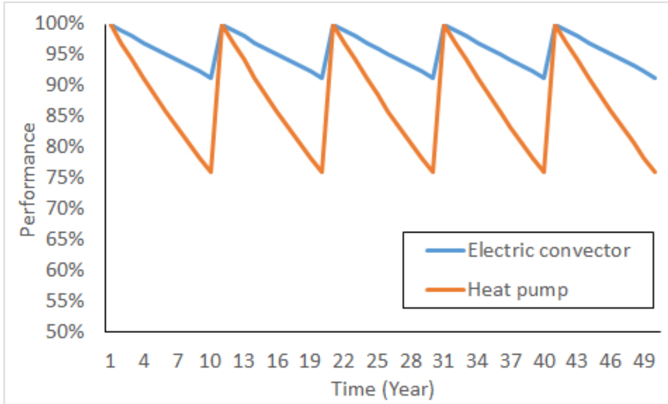


Figure 4-7: Model examples of the temporal evolution of the technical performance of electric convector (blue) and heat pump (orange) with system replacements every decade over the lifecycle of the building (estimated by (Hendron and Paper, 2006))

4.4.2 Technological progress

Given the long lifetime of buildings, technology changes and improvements are inherent during this period. The integration of some technology potential improvements in DLCA is challenging. Technological progress can be present during the use phase (maintenance, replacement, renovation). Besides, the background system such as infrastructure, products fabrication processes, waste treatment technologies can be improved to reduce their environmental impacts at a long time scale.

According to the Energy transition law for the green growth (LTECV: La loi de transition énergétique pour la croissance verte in France), actions for promoting circular economy are growing in France the last few years with goals for recycling and waste technologies settled until 2025 ("la loi de transition énergétique pour la croissance verte en actions" 2016). Following this French law, the commitment to green growth related to flat glass was signed in 2017 and fixed the increase of cullet content in the glass as a 2025's goal. We created a data set (like ecoinvent module) for future windows considering the increase from 30% to 50%, and also accounting for energy consumption gain by 2.5% per 10% increase of the cullet ("Engagement pour la croissance verte du 26 octobre 2017 relatif au recyclage du verre plat de déconstruction et de rénovation" 2017).

Reducing wastes and increasing recycling rates of the building materials are also important factors to meet our targets with regard to LTECV. In this study, we investigate the influence of an increase in recycling rate for certain construction products on LCA results comparing to the end-of-life scenario given by EPDs as the reference. Our case study investigates the influence of the evolution from current recycling to future one on LCA results for construction products based on concrete, steel, aluminum and wood used for the building.

We also assumed improvements for the most electricity consuming fabrication processes of building products by introducing 10% reduction every decade, following an expert opinion (Chevalier, 2018). The concerned industrial sectors are the fabrication of aluminum, steel, and concrete, regarding building materials and HVAC equipment replaced during the building use phase. Energy flow analysis was first conducted through a network of the case study in order to identify important energy consumer processes for which a 10% reduction of energy consumption is possible. Then, we selected only a few processes for which electricity consumption was modified in time. This simplification is necessary because the present case study is composed of more than 10 000 processes and more than 300 000 supplies between processes, and replacing every module of energy consumption process of all the system network by updated energy consumption model is actually impossible.

Prospective aspects taken into account in this case study concern only a small part of the building-related technologies. Also, as mentioned in Section 2.3.2, the temporal characteristics of prospective aspects depend on the time scale of the studied system and the scope of the study. In this case study, the prospective aspects were limited to those described here above. Other technological innovations such as future HVAC system or energy efficiency improvement for other industrial sectors are excluded.

4.4.3 Change in family size

The family size is a parameter evolving over time and has consequences on energy consumption. Changing the inhabitant number leads to a change in the indoor heat gain from the human body and DHW needs, to be integrated into electricity load calculations. The only information we have concerning the structure of the family is that there are 15 inhabitants in three houses. Therefore, we took a hypothesis on the basis of the national statistic survey in France (INSEE, 2017) that each family includes two parents and three children from 2015 to 2035. We considered an average number of inhabitants deduced for a building habitable surface to calculate electricity consumption for heating. To obtain DHW needs, French thermal regulation 2012 introduced the notion of the number of equivalent adults. The number is calculated concerning a building's habitable area that also defines the maximal number of inhabitants (CSTB, 2011). One considers that one adult consumes 500 little a week at 40° C, which is set by default for the calculation complying with the French Thermal regulation.

Mathematical formulas to calculate an adequate number of adults N_{adeq} are as follows:

$$N_{max} = \begin{cases} 1 & si \quad A_{gr} < 30m^2 \\ 1.75 - 0.01875 \times (70 - A_{gr}) & si \quad 30m^2 < A_{gr} < 70m^2 \\ 0.025A_{gr} & si \quad A_{gr} \geq 70m^2 \end{cases} \qquad Equation\ 4\text{-}1$$

And,

$$N_{adeq} = \begin{cases} N_{max} & si \quad N_{max} < 1.75 \\ 1.75 + 0.3 \times (N_{max} - 1.75) & si \quad N_{max} \geq 1.75 \end{cases} \qquad \textit{Equation } 4\text{-}2$$

With $N_{\max}$ for a maximal number of occupants for a habitable area A_{gr} (m^2).

The estimated number of occupants is then used to calculate internal heat gain (radiative and convective) and internal humidity gain due to the presence of occupants in a building. Moreover, heating needs for the building are calculated combining technical performances of a building system and the number of occupants. More details of the calculation method are described in CSTB (2011).

4.4.4 Evolution of the French electricity mix

The French energy transition law for green growth is set out as a national strategy including ambitious targets in 2015, in order to ensure the security of energy supply, sustainable development, and energy economy. The law proposes medium- and long-term objectives as French national strategy on the reduction of final energy consumptions and GHG emissions by introducing renewable energy sources into electricity production instead of fossil fuel and nuclear power. More precisely, the French government aims at reducing GHG emissions to fulfill the target of 40% emission decrease until 2030 compared to 1990. The following approaches are set out: decrease in fossil fuel consumption by 30% until 2030, reduction of the share of nuclear (that is currently occupying 85% of electric grid) by 50% until 2025, and an increase in the share of renewable sources by 32% of final energy consumption up to 2030. (“La loi de transition énergétique pour la croissance verte en actions” 2016).

The current practice of LCA uses an annual average mix of electricity production for the entire lifecycle of studied systems. At the contrary, the present work includes future scenarios of French electricity mix developed by the French Environment & Energy Management Agency (ADEME in French) (ADEME, 2017) with the aim of investigating how a future change of electricity production mix affects LCA results. Different scenarios were proposed at the horizon of 2035 and 2050 in order to meet the LTECV targets.

The current mix scenario composition is retrieved from historical data of ADEME for 2010. It contains 72% of nuclear electricity. Whereas ADEME’s scenarios assume future developments of new energies such as marine energy and geothermal energy, the ecoinvent database does not possess datasets for this kind of processes. For this reason, these new energies are not included in our study, but instead, their % contribution was allocated to the French annual average mix of a given year. While being aware of this lack of data, we considered two scenarios of the future production mix: the one with the high nuclear share of 50% in 2050 and another one with a brutal shift of nuclear share to around 5% in 2050. Hereafter, we call these two scenarios “Mix-50% Nuclear” and “Mix-90% RE&Gaz”, respectively. Figure 4-8 represents the base mix in 2010 and the two scenarios with their respective shares at two horizons, 2035 and 2050.

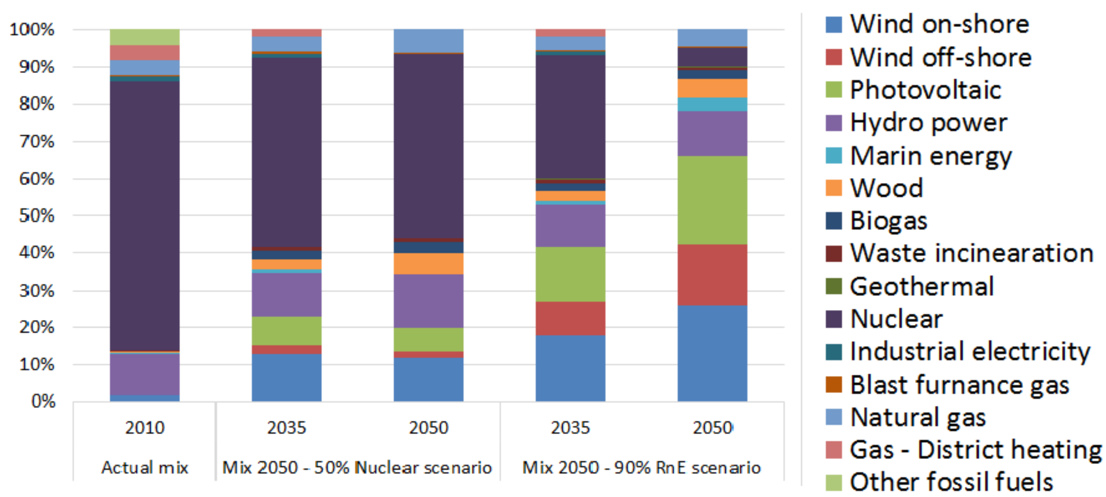


Figure 4-8: Mix scenarios of French electricity production for three distinct time horizons (current, 2035 and 2050)

For this case study, the use phase of the building is segmented into three distinct periods of 2015-2034, 2035-2049 and 2050-2065 to which the current mix 2010, the mix 2035 and the mix 2050, for two scenarios, are applied.

LCI models of the future mix were developed using existing ecoinvent 3.2 data. This fact implies that technologies and infrastructures for energy generation do not evolve over the lifecycle of the building, which represents a limiting assumption of the approach. The future mix is modelled only by varying mix composition without changing the current technologies.

In order to develop LCI models for the future mix, it is important to understand how the module of electricity production in ecoinvent is modeled. Figure 4-9 shows the ecoinvent model for 1kWh electricity production. The model considers different voltage levels (high, medium and low levels) and technologies of different energy sources and includes electricity losses related to the transmission (at high and medium voltage), conversion (from high to medium and from medium to low voltage) and distribution. Following this model, future electricity production model for 2035 and 2050 are developed by introducing a temporal variation of the resource share.

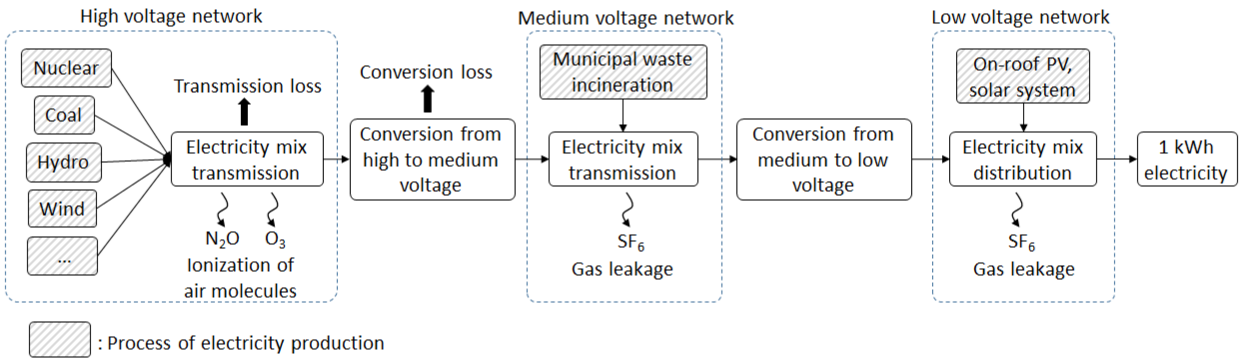


Figure 4-9: Ecoinvent model of the module of 1kWh electricity production

For the reason of the complexity of modelling, the application of the future mixes is limited to end-use energy consumptions and processes in the background system such as product fabrications, transport or infrastructures are based on the current mix, i.e., the same LCI data is used for the technologies of electricity production. Also, it should be noted that our prospective mix of electricity production is considered as an annual average value, while in reality, electricity production mix is variable even at hourly time steps. The methodological challenge of taking into account the short-term variability of electricity mix and its influence on LCA results have been studied by Fouquet et al. (2015), for example.

4.4.5 Summary of temporal parameters and scenarios

Table 4-6 resumes the variable parameters considered in the dynamic LCI modelling. For each temporal parameter, a possible maximal range of values was considered as “Best” and “Worst” case. More detailed scenario description is found in Table 4-7. For certain products, the baseline scenario already represents the worst case scenarios, and in that case, scenario analysis is effectuated only for the baseline and the prospective scenarios.

Table 4-6: Summary of time-varying parameters of the building system taken into account in the case study

Parameter group	Parameters	Values	How to integrate	References
Structure of the family	Number of occupants	15 (2 adults and 3 children per family) for 2015 to 2035, then 6 (adults) for 2035 to 2065	Dynamic Thermal Simulation (DTS), then energy in LCI	(INSEE, 2017)
	Age of occupants	Adults or children	Defined in compliance with French Thermal Regulation 2012 method and integrated into DTS to calculate DHW demand, then energy in LCI	(CSTB, 2011)
Degradation of building materials and efficiency of energy equipment	Heat transfer coefficient of insulation materials	Increase of 0.5% per year with respect to a preceding year	DTS, then energy in LCI	(Stazi et al., 2014; Eleftheriadis and Hamdy, 2018a)
	Energy efficiency of electric convector	Decrease of 1% per year with respect to a preceding year	DTS, then energy in LCI	(Hendron and Paper, 2006)
	Coefficient of performance (COP) of heat pump	Decrease of 3% per year with respect to a preceding year	DTS, then energy in LCI	(Hendron and Paper, 2006)
Technological progress	Window type	PVC window	Material and energy inventory in LCI	National strategy for green growth ("la loi de transition énergétique pour la croissance verte en

		Increase up to 50% of cullet use in glazing		actions” 2016; “engagement pour la croissance verte du 26 octobre 2017 relatif au recyclage du verre plat de déconstruction et de rénovation” 2017)
	Insulation materials	Bio-based and recycled insulation materials	Material and energy inventory in LCI	(Choi et al., 2018; Stazi et al., 2014)
	Energy consumption of product fabrication processes	Decrease by 10% of energy every decade	Material and energy inventory in LCI	(Chevalier, 2018)
	End of life technology	Recycling rate	LCI modelling	EPDs, literature reviews
French energy mix change	Composition of resources/technologies for electricity production in the French grid mix	Scenario ADEME 2035 and 2050: Mix-50% Nuclear (50% share of nuclear energy in 2050), Mix-90% RE&Gaz (90% share of renewable energy in 2050)	Material and energy inventory in LCI	(ADEME, 2017)

Table 4-7: Prospective scenarios taken into account in the case study

<table>
<tr><th colspan="2" rowspan="2">DYNAMIC ASPECT</th><th rowspan="2">PRODUCT</th><th colspan="2">BASELINE</th><th colspan="2">WORST CASE</th><th colspan="2">BEST CASE</th></tr>
<tr><th>Scenario name</th><th>Scenario description</th><th>Scenario name</th><th>Scenario description</th><th>Scenario name</th><th>Scenario description</th></tr>
<tr><td rowspan="3">Technological advancements</td><td rowspan="2">Innovation on insulating material</td><td rowspan="3">Insulation</td><td rowspan="3">Insulation, baseline</td><td rowspan="3">- Year 0: 546 kg of rock wool, 4984 kg of glass wool and 483 kg of polyurethane
- Year 30: same types, same amount
- Year 50: 100% landfill (FDES)</td><td rowspan="2">Insulation, worst case</td><td rowspan="2">- Year 0: 546 kg of rock wool, 4984 kg of glass wool and 483 kg of polyurethane
- Year 30: replacement 100% by extruded polystyrene (HFC blown) - 5099 kg
- Year 50: 100% landfill</td><td>Insulation, best case, bio based</td><td>- Year 0: 546 kg of rock wool, 4984 kg of glass wool and 483 kg of polyurethane
- Year 30: replacement 100% by bio based material - 16835 kg of cork slab
- Year 50: 20% recycled and 80% landfill</td></tr>
<tr><td>Insulation, best case, recycled</td><td>- Year 0: 546 kg of rock wool, 4984 kg of glass wool and 483 kg of polyurethane
- Year 30: replacement 100% by recycled material - 3263 kg of EPS 100% recycled
- Year 50: 100% recycling</td></tr>
<tr><td>End of life progress</td><td colspan="2">The worst case is represented by baseline (100% landfill)</td><td>Insulation, recycling</td><td>- Year 0: 546 kg of rock wool, 4984 kg of glass wool and 483 kg of polyurethane
- Year 30: same types, same amount
'- Year 50: 100% recycling of all materials</td></tr>
<tr><td>Technological advancements</td><td>Innovation on material</td><td>Windows</td><td>Windows, baseline</td><td>- Year 0 - PVC windows installation (with 30% of glass cullet)
- Year 30 - Refurbishing, 100% landfill of old windows and new PVC windows installation
- Year 50 - Glazing: 95% landfill</td><td colspan="2">The worst case is represented by baseline (no progress in recycled content of glazing or PVC)</td><td>Windows, recycled content in glazing</td><td>- Year 0 - PVC windows installation
- Year 30 - Refurbishing, 100% landfill of old windows and new PVC windows installation (the glazing containing 50% of cullet)
- Year 50 - Glazing: 95% landfill and 5% recycling / PVC frame: 92.1% landfill and 7.9% recycling</td></tr>
</table>

	End of life progress			and 5% recycling / PVC frame: 92.1% landfill and 7.9% recycling	**Windows, landfill**	- Year 0 - PVC windows installation - Year 30 - Refurbishing, 100% landfill of old windows and new PVC windows installation '- Year 50: 100% landfill of all materials	**Windows, recycling**	- Year 0 - PVC windows installation - Year 30 - Refurbishing, 100% recycling of old windows and new PVC windows installation - Year 50 - 100% recycling
Technological advancements	**End of life progress**	**Heat Pump and Electric Convector**	**HVAC, baseline**	- Year 0 - Installation of Heat Pump - Every 10 years - 100% landfill of old heat pump and installation of a new heat pump - Every 15 years - 80% recycling, 10% incineration, and 10% landfill of old electric convector and installation of a new electric convector -Every 17 years - 100% landfill of an old ventilation system and installation of a new ventilation system	**HVAC, landfill**	- Year 0 - Installation of Heat Pump - Every 10 years - 100% landfill of old heat pump and installation of a new heat pump - Every 15 years - 100% landfill of old electric convector and installation of a new electric convector -Every 17 years - 100% landfill of an old ventilation system and installation of a new ventilation system	**HVAC, recycling**	- Year 0 - Installation of Heat Pump - Every 10 years - 100% recycling of old heat pump and installation of a new heat pump - Every 15 years - 100% recycling of old electric convector and installation of a new electric convector -Every 17 years - 100% recycling of old ventilation system and installation of a new ventilation system
		Concrete products	**Concrete products, baseline**	There are 8 construction products whose main material is concrete. The baseline scenario gathers these products, considering the end of life as specified in each EPD. - Year 0 - installation of: - Manhole, - Concrete slab for road network, - Concrete paving block, - Bedding concrete, - Concrete shuttering block, - Precast concrete slab,	**Concrete products, landfill**	There are 8 construction products whose main material is concrete. The landfill scenario gathers these products, considering the end of life as landfill. - Year 0 - installation of: - Manhole, - Concrete slab for road network, - Concrete paving block, - Bedding concrete, - Concrete shuttering block, - Precast concrete slab,	**Concrete products, recycling**	There are 8 construction products whose main material is concrete. The landfill scenario gathers these products, considering the end of life as recycling. - Year 0 - installation of: - Manhole, - Concrete slab for road network, - Concrete paving block, - Bedding concrete, - Concrete shuttering block, - Precast concrete slab, - Exterior wall in concrete,

				- Exterior wall in concrete, - Floating screed. - Year 50 - EPD scenario		- Exterior wall in concrete, - Floating screed. - Year 50 - LANDFILL		- Floating screed. - Year 50 - RECYCLING
		Wood products	**Wood products, baseline**	There are 5 construction products whose main material is wood. The baseline scenario gathers these 5 products, considering the end of life as specified in each EPD. - Wooden fence, - Wooden floor, - Wood cladding, - Resinous frame, - Wall, timber frame. - Year 50 - EPD scenario	**Wood products, incineration**	There are 5 construction products whose main material is wood. The baseline scenario gathers these 5 products, considering the end of life as incineration. Year 0 - installation of: - Wooden fence, - Wooden floor, - Wood cladding, - Resinous frame, - Wall, timber frame. - Year 50 - INCINERATION	**Wood products, recycling**	There are 5 construction products whose main material is wood. The baseline scenario gathers these 5 products, considering the end of life as recycling. Year 0 - installation of: - Wooden fence, - Wooden floor, - Wood cladding, - Resinous frame, - Wall, timber frame. - Year 50 - RECYCLING
		Steel products	**Steel products, baseline**	There are 6 construction products whose main material is steel. The baseline scenario gathers these products, considering the end of life as specified in each EPD. Year 0 - installation of: - Wood door with metal frame, - Steel cladding, - Metallic sheet, - Precast concrete slab, in reinforced concrete, - Exterior wall, - Floating screed, in reinforced concrete.	**Steel products, landfill**	There are 6 construction products whose main material is steel. The baseline scenario gathers these products, considering the end of life as landfill. Year 0 - installation of: - Wood door with metal frame, - Steel cladding, - Metallic sheet, - Precast concrete slab, in reinforced concrete, - Exterior wall, - Floating screed, in reinforced concrete.	**Steel products, recycling**	There are 6 construction products whose main material is steel. The baseline scenario gathers these products, considering the end of life as recycling. Year 0 - installation of: - Wood door with metal frame, - Steel cladding, - Metallic sheet, - Precast concrete slab, in reinforced concrete, - Exterior wall, - Floating screed, in reinforced concrete. - Year 25 - RECYCLING for end of life of doors and steel cladding and installation of

				- Year 25 - EPD scenario for the end of life of doors and steel cladding and installation of new ones. - Year 50 - EPD scenario for EoL.		- Year 25 - LANDFILL for end of life of doors and steel cladding and installation of new ones. - Year 50 - LANDFILL		new ones. - Year 50 - RECYCLING
Technological advancements	**Energy consumption of product fabrication processes**	-	**Baseline**	Energy consumption of product fabrications processes in the background system is maintained (ecoivnent raw data)	-	-	**Energy consumption for the background processes, best case**	Products for which the scenario of 10% decrease in energy consumption for their fabrications are applied: - Electric convector - Heat pump - Insulation - Metal sheet - Insulation - PVC slabs - Roller shutter - Windows
Technological advancements	**Future Energy mix**	-	**Actual energy mix**	Period 2015 – 2065 years: - French annual average mix using ecoinvent data “electricity, low voltage {FR}| market for”	**Energy mix, ADEME, worst case**	Period 2015 – 2035 years: - French annual average mix using ecoinvent data “electricity, low voltage {FR}| market for” Period 2035-2065 years: - “Mix-50% Nuclear’ scenarios of ADEME for 2035-2050 and 2050-2065	**Energy mix, ADEME, best case**	Period 2015 – 2035 years: - French annual average mix using ecoinvent data “electricity, low voltage {FR}| market for” Period 2035-2065 years: - “Mix-90% RE&Gaz” scenarios of ADEME for 2035-2050 and 2050-2065

4.5 Results and discussion

4.5.1 Results for the entire building

First, the results obtained with the static LCA for global warming potential are analyzed. To generate LCA results, SimaPro software and ecoinvent 3.2 dataset were used for LCI modelling and with characterization factors for the climate change impact assessment following the IPCC model retained by the EN15804 and EN15978 standards. GWPs of GHGs were used for a 100-year time horizon (GWP100). This method will always be considered as a reference to which dynamic LCA results will be compared. In Figure 4-10, we observe that the "construction products" contributor dominates the impact, followed by "energy consumptions" for house holdings during the building's use phase.

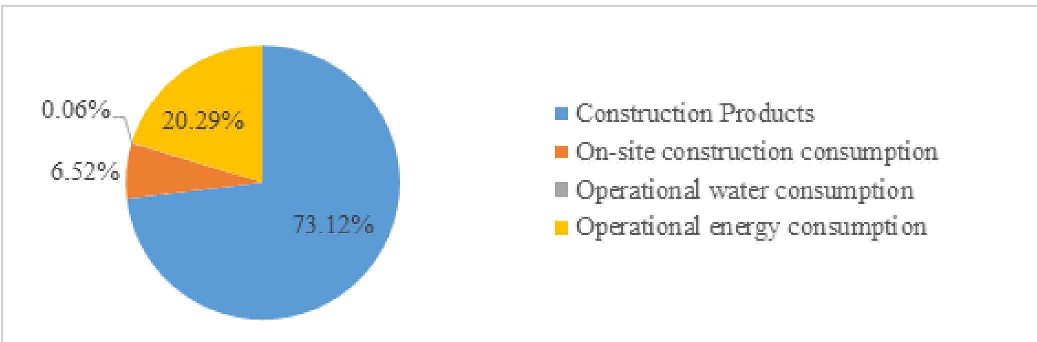


Figure 4-10: Building's contributors to the climate change based on conventional LCA method

Table 4-8 shows the comparison of the LCA results between ELODIE / EPDs model and SimaPro / ecoinvent model. The total value of global warming is 3.35E+05 kgCO2 eq. obtained with ELODIE and 4.17E+05 kg CO2 eq. obtained with SimaPro. Considering the results at the contributor level, we can observe that the most important difference is due to construction products with 37% higher for SimaPro model. We observed that the difference in the construction products contributor comes mostly from processes of insulation materials and concrete products. Both SimaPro model and ELODIE model were modeled by following EN15804 standard and both respects "cradle to grave" LCI modelling. Thus, there is no difference in the system boundaries. At this point, our objective is not to deepen the analysis of this result discrepancy. However, this aspect should be treated as a future work to improve inventory datasets of the building sector.

Table 4-8: Comparison of climate change impact results obtained with ELODIE and SimaPro

Contributors	ELODIE model kg CO_2 eq (contribution %)	SimaPro model kg CO_2 eq (contribution %)
Construction products	2.23E+05 (66.9%)	3.05E+05 (73.1%)
Operational energy consumption	8.78E+04(26.3%)	8.47E+04 (20.3%)
Operational water consumption	1.73E+02 (0.1%)	2.69E+02 (0.1%)
On-site construction consumption	2.23E+04 (6.7%)	2.72E+04 (6.5%)
Total life cycle (kg CO_2 eq.)	3.33E+05	4.17E+05

"Energy consumptions" contributor represents only 20% of the total impact, with SimaPro model. This value seems to be very low comparing to other conventional studies. However, according to the study in the framework of "HQE performance" project in France, operational energy consumption represents only 30% of climate change impact, for 40 individual houses (Lebert et al., 2013). In our case, when converting the building LCI model obtained with ELODIE/EPDs to a SimaPro/ecoinvent model, the part of impact for "construction products" increased. Therefore, "energy consumption" contributor based on ecoinvent data represents a slightly lower value than the former model.

In the following, dynamic LCA for climate change impact calculation was performed in two conditions:

- First, by excluding biogenic CO2 from LCI, in order to account for the same GHG as the classical LCA – EN15804 and EN15978. In this way, differences between static and dynamic approaches are easier to understand.
- By accounting biogenic CO_2 in all processes, as emissions (e.g., incineration of biomass) and uptake for photosynthesis.

In all cases, three indicators were calculated: instantaneous radiative forcing, cumulative radiative forcing, and global mean temperature change.

Figure 4-11 shows the results obtained in the first condition, i.e., without biogenic CO2.

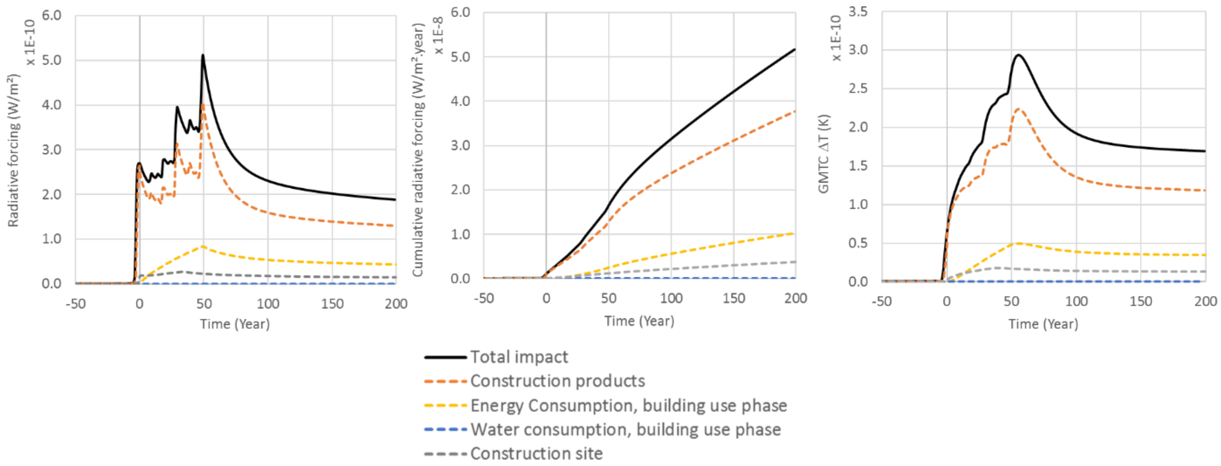


Figure 4-11: Dynamic impacts of 4 contributors over the lifecycle of the studied building (without biogenic CO2)

As can be seen in the three graphs, the time horizon is an important factor for the results interpretation. One observes product replacement peaks during the 50 years of building life and the end-of-life peak. For the three impact categories and throughout the years, construction products are the most impacting contributor followed by energy consumption.

These results were compared to classical LCA with IPCC 2013 method (GWP100 years), complying with the Standard EN 15978 (LCA method applied to buildings). Figure 4-12 presents the contributions of each building contributor to global warming, obtained with conventional and dynamic LCA. In terms of dynamic analysis, the cumulative radiative forcing (W/m².year) and the global mean temperature change (K) were calculated for a time horizon of 100 years (building construction is considered to occur at time zero); thus results are presented for the same time horizon.

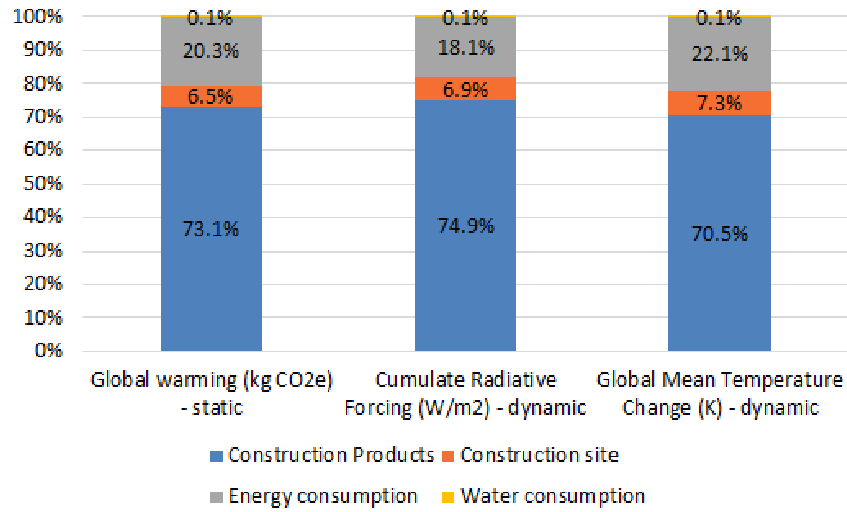


Figure 4-12: The contributors to climate change indicators (without biogenic CO2)

As expected, the results are quite similar since the contribution of GHG emissions from the 4 contributors is the same in conventional LCI and dynamic LCI. We remind here that the inventory is common for the two methods (obtained with SimaPro); the difference lies in its distribution on the timescale. The small differences observed in % of contribution are due to the difference in time of emissions: emission at zero time in conventional LCA, emissions distributed in time for dynamic LCA. Worth noting that there is no information from conventional result about the impact timing: when does it occur, are there peaks, effect persistence in time, etc.?

Considering the capture (tree growth) and emission (wood incineration) of biogenic CO_2 overall in the life cycle system, a more realistic picture is obtained because some arbitrary assumptions (i.e., fixed time horizon like in conventional LCA, the neutrality of biogenic CO_2) were given up. Here 81 types of emissions with a combination of the chemical substances, compartment, and sub-compartment are evaluated for their three dynamic impact indicators. Comparative results are presented in Figure 4-13. With these processes, the results at 100th year are lowered by 22% for radiative forcing, by 34% for cumulative radiative forcing and by 23% for the global mean temperature change.

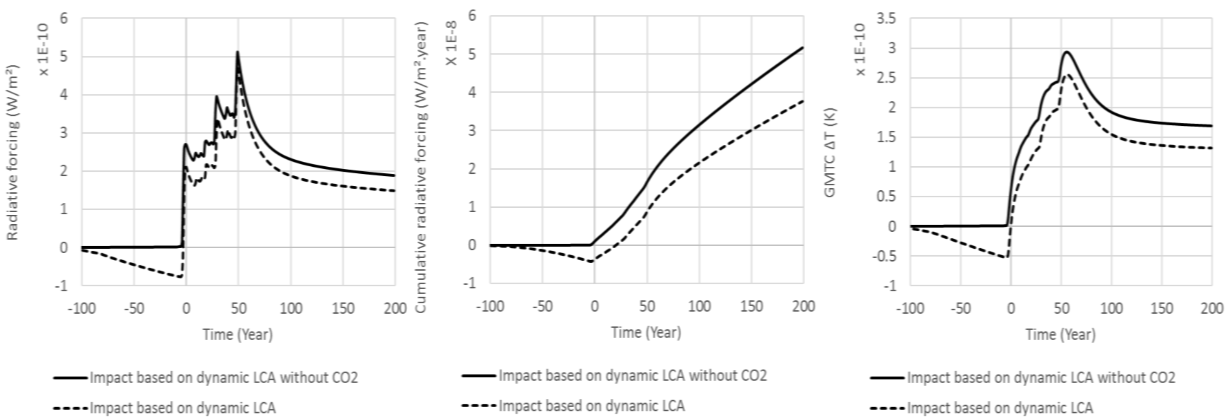


Figure 4-13: Climate change dynamic impact of building including or not biogenic CO_2 in LCI

Finally, the results obtained with DLCA including biogenic carbon, for the entire building system and the 4 contributors are presented in Figure 4-14. It is possible to follow the evolution of each indicator and to note that the major contribution is attributed to construction products and operational energy starting from time zero. Before this milestone, the net impact of the building system is due to construction products and is a benefit impact (indicators have negative values) due to wood raw material. Comparison with static LCA global warming is presented in Figure 4-15. The ranking of the contributors is the same whatever the indicator and LCA method. However, it is obvious that fixing a point in time (e.g., 100 years) cannot provide the full information, which is very rich in case of dynamic indicators. By a graph representation versus time, it is possible to conclude that the effect of emissions at a given moment (e.g., time zero) will have repercussion on the cumulative indicator CRF, which stores the history of the emissions. GMTC versus time informs about the direct impacts of emission which appear several years after the emission (delay which depends on the nature of the gas).

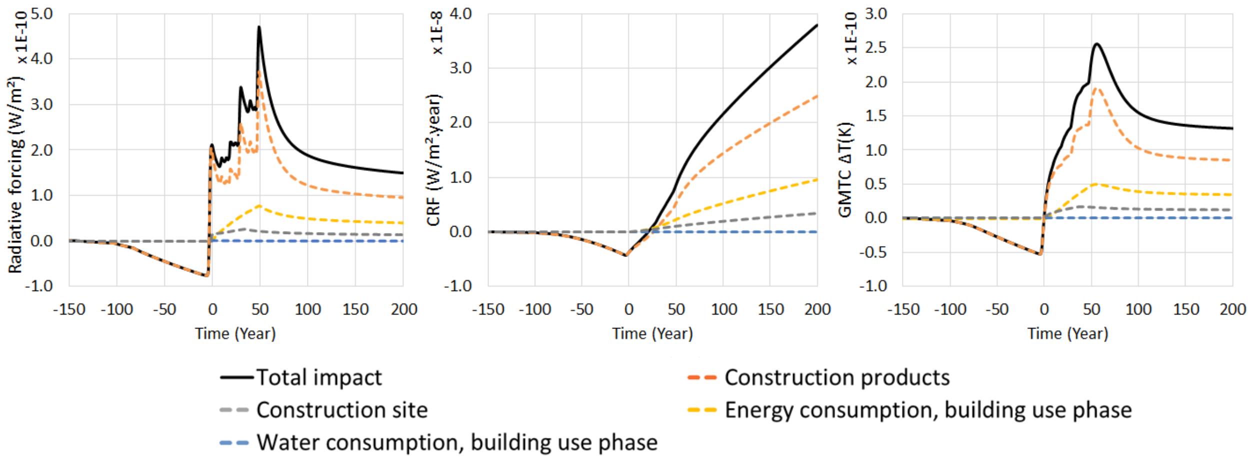


Figure 4-14: Climate change dynamic impact (including biogenic CO_2) for the entire building system and for the 4 contributors

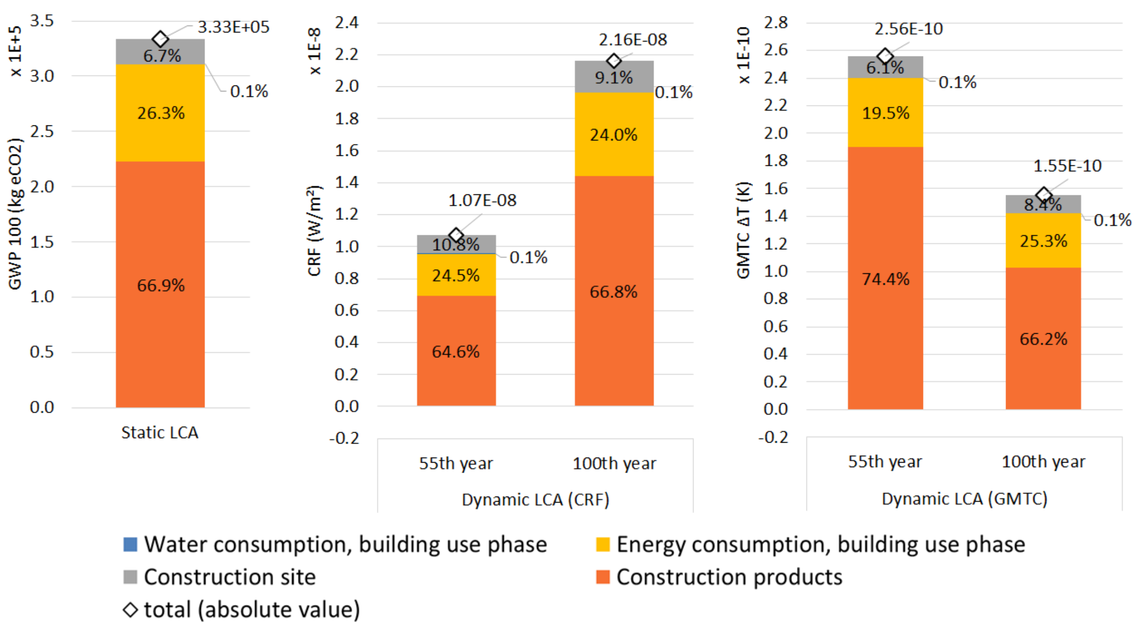


Figure 4-15: Comparison of climate change results obtained with static LCA and DLCA. Entire building system and the 4 contributors.

4.5.2 Contribution of construction products

As seen in the previous section, construction products are the major contributor to climate change compared to other contributors through the whole building lifecycle, for both conventional and dynamic LCAs. In order to identify hotspots of climate change impact, the analysis was performed by family of products (Figure 4-16). Comparisons between conventional and dynamic LCA results are also performed. Starting from this section and for the following results presentations, every dynamic analysis will be conducted by including the effect of biogenic CO2 (emitted from biomass) and captured CO2 from the atmosphere (for biomass growth).

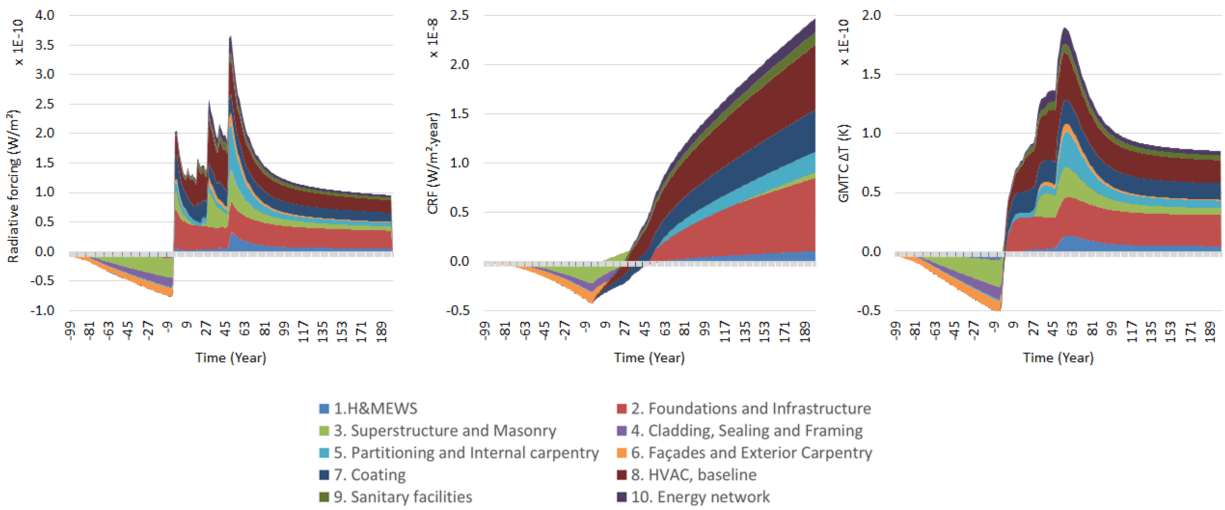


Figure 4-16: Contribution analysis of construction product family to dynamic impacts

As seen in Figure 4-16, the net negative effect begins around 100 years back from the construction time, corresponding to the start year of tree growth in this case study. The Foundations and Infrastructures family, the HVAC family, the Coating family are the three major contributors to climate change impact over a long period. This is due to the important GHG emission and the persistence of emitted CO_2 in the atmosphere with very long term effect.

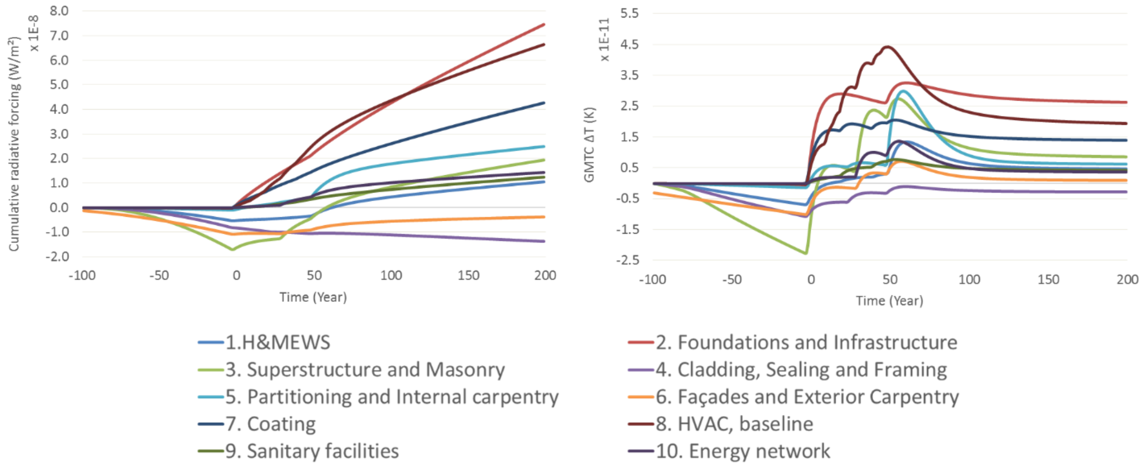


Figure 4-17: Dynamic impacts of 10 families of construction products

Figure 4-17 illustrates individually the dynamic impact behavior of each construction product family for CRF and GMTC indicators. The peak temperature due to the HVAC family (dark red) is the highest one. The temperature increase due to the F&I family persists for a long period and is 33% higher than those of HVAC family at the 150^{th} year. Partitioning and Internal carpentry, P&IC (clear blue), presents an important increase at the end-of-life phase, but the temperature also declines rapidly. This fact can be explained by making the analysis of the contribution to the impact of each chemical substance. At the end-of-life stage of P&IC, methane is identified as a gas dominating the impact, emitted in the landfill scenario for plasterboard waste. The landfill generates methane by decomposing organic materials, including wood in our case. As the atmospheric concentration of methane emitted from landfill declines faster than other major GHG, radiative forcing due to methane is not persistent for a long time scale.

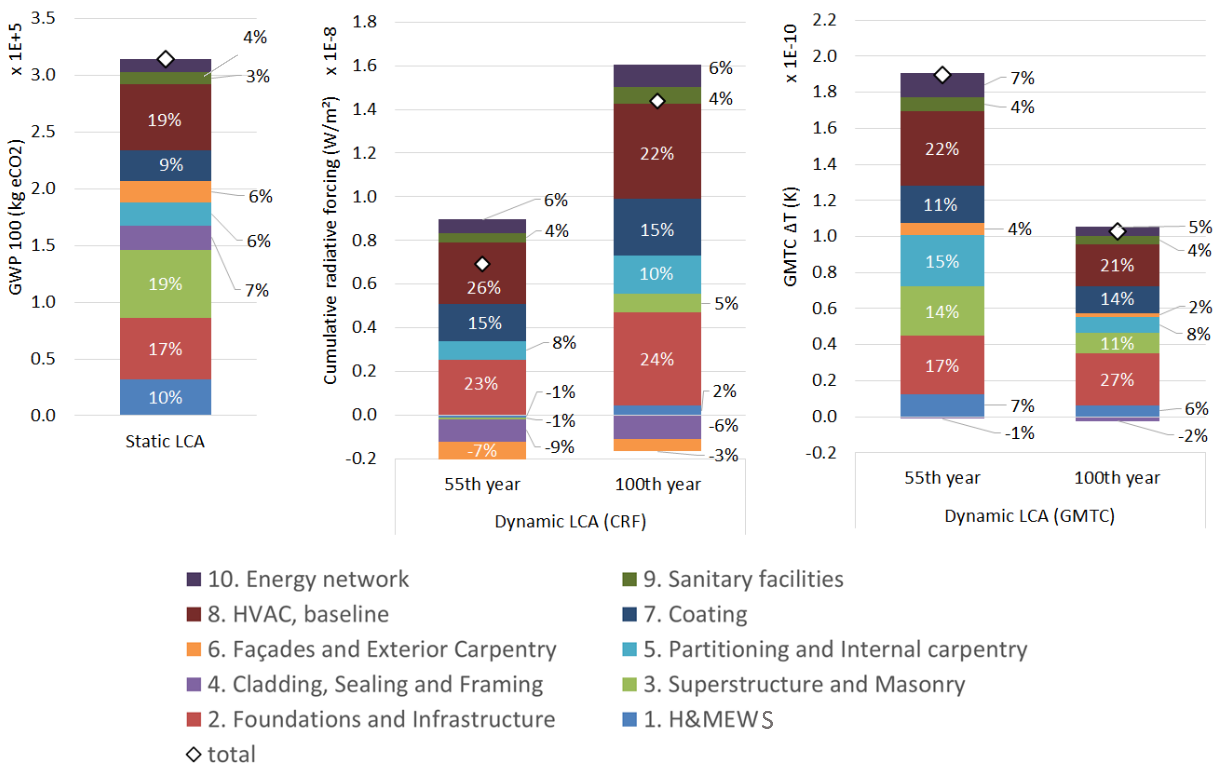


Figure 4-18: Comparison of impacts of construction products families according to different LCA methods

Figure 4-18 shows the comparison of relative contributions of each product family to different LCA metrics. For this comparison, GWP100 was used for conventional LCA. Cumulative radiative forcing and global mean temperature change were calculated for dynamic LCA at 55th and 100th years. The temperature peak appears several years later than the moment of GHG emission, due to the thermal inertia of the planet. This time lag depends on the gas nature. The overall increase in temperature attains a peak at around 55th in our case study as seen in Figure 4-16, i.e., several years later than the last emission at the end of the building lifecycle (end of life). This is the reason why the 55th year was chosen as a time horizon for the impact analysis.

Globally looking at the results in these three graphs, there are some changes of contribution rankings between different LCA metrics, e.g., F&I group slightly increases from 19% in conventional to 25% in dynamic while the 2nd and 3rd groups alternate their rank. However, S&M, F&I and HVAC are always the most impacting groups for the three indicators. At the contrary, contributors involving biogenic carbon in their inventories, i.e., Façade and exterior carpentry, have a negative contribution on CRF and few contributions on GMTC, diminishing in time. The cause of that behavior is the biogenic carbon captures by trees. Some other groups also have a significant amount of wood products (e.g., S&M). However the effect of biogenic carbon capture is drowned out by GHG emitters like processes for cement production.

Moreover, we see for the group F&EC (orange in Figure 4-18) that, while CRF is a negative value, GMTC goes to a positive value. This aspect is analyzed in more detail in the following part focusing on each construction product family.

A first conclusion is that, for a studied system: i) CRF indicator always increases due to the persistence of GHG in the atmosphere beyond the lifetime of the system; ii) GMTC is critical during the lifetime of the system prolonged with several years.

Consequently, a relevant time horizon for impact observation could be the lifetime of the system plus several years beyond (up to ten).

The following part is dedicated to the impact analysis by family of construction products. For each family, dynamic impacts are calculated with three dynamic LCA models:

- The first one called "DLCA0" is a model in which all emissions are considered to happen at time 0 as a Dirac function, and the impacts are calculated in function of time. Also, CO_2 uptake by plants and biogenic CO_2 emissions are not integrated.
- In model "DLCA1" the emissions are distributed over time following the specificities of the building's lifecycle and biogenic CO_2 is not considered.
- The third model called "DLCA2" uses the DLCA approach proposed in this work as an alternative to conventional LCA.

DLCA0 and DLCA1 models are developed for the sake of understanding how the temporal distribution of LCI can affect the LCA results. Table 4-9 resumes these different models.

Table 4-9: Description of dynamic models

Model name	LCI modelling	CO_2 uptake by plants and Biogenic CO_2
DLCA0	All emissions at time 0	No
DLCA1	Emissions distributed over time	No
DLCA2	Emissions distributed over time	Yes

The comparison of the results is performed for the 3 climate change metrics, i.e., for RF (W/m^2), CRF (W/m^2.year), and GMTC (K). Results are analyzed in a short and long time scale identifying hotspots in order to provide effective mitigation solutions. For the analysis of the results, attention is paid to the temporal profile of the climate indicators such as the amplitude, time-scale, and impact rate. Then, impacts calculated with DLCA2 only are analyzed in order to understand how the major GHGs influence the amplitudes and positions of impacts on the timescale.

4.5.2.1 Highways and miscellaneous external works

This family group includes concrete paving block, drainage and sewage networks, wooden fence, exterior cladding, concrete slab for the road network and manhole. According to conventional LCA results, the most impacting product is the exterior cladding, which accounts for 59% of total emissions in terms of CO2 equivalent of this family group.

Figure 4-19 shows dynamic impacts as radiative forcing RF, cumulative radiative forcing CRF and global mean temperature change GMTC.

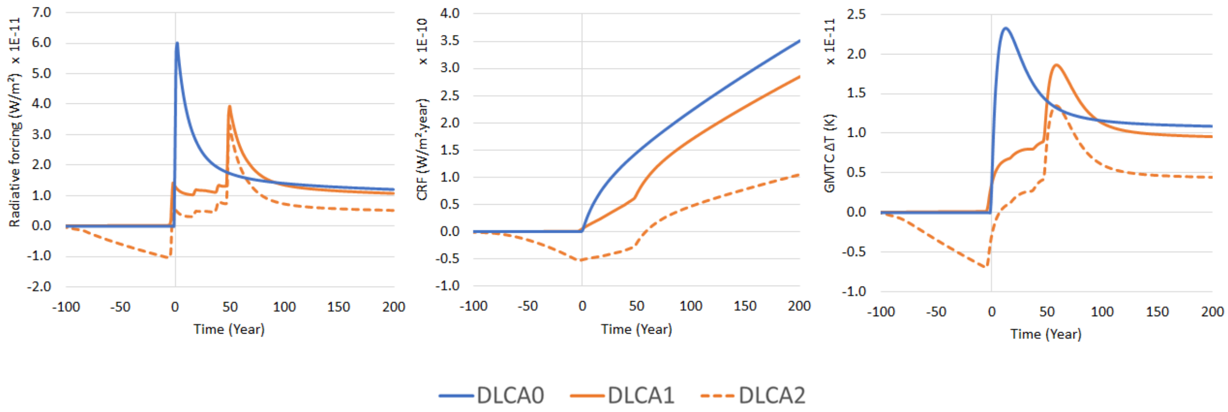


Figure 4-19: Comparison of DLCA results for H&MEW group following models DLCA0, DLCA1, and DLCA2

The replacement of exterior cladding every 20 years can be observed on the dynamic emission models DLCA1 and DLCA2. Static emission model DLCA0 estimates higher impacts than DLCA1, which means that an assumption of putting all emissions at the first year overestimates impacts comparing to DLCA1 that distributes emissions over time. The CRF in the 100th year for DLCA1 is 23% lower than for DLCA0 and GMTC for DLCA1 is 20% lower than for DLCA0.

An important conclusion is that the same quantity of GHG emission has a lesser impact when the emission is spread over a long time interval as if the emission is released instantaneously.

As expected, if we consider the effect of biogenic CO_2, the differences between different impact metrics are even more accentuated (59% for CRF and 46% for GMTC). Temperature attains its peak at 62 years with the value of 2.0E-11 K for DLCA2.

These results emphasize that the proposed dynamic model is thus able to account for the beneficial (or negative) effect of biogenic CO_2, depending on the process.

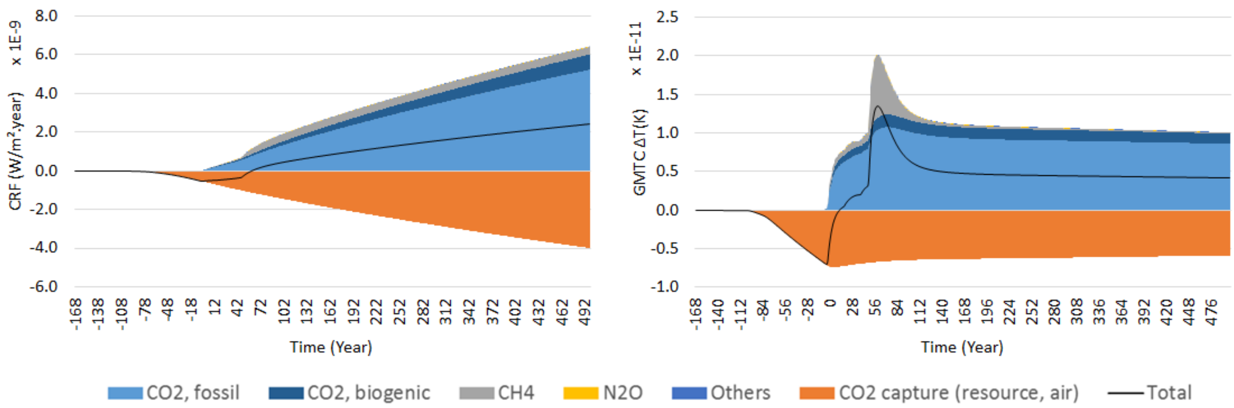


Figure 4-20: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) and GMTC (K)) for H&MEW group

Following Figure 4-20, the major GHG contributors to the impact intensity are fossil CO_2, biogenic CO_2 emitted, and CH_4. A high peak of temperature is due to CH_4 emissions at the end of life stage, from waste landfills, but this effect disappears several years after its emission. We can also conclude that the long-term temperature change (GMTC) is due to CO_2 emissions counterbalanced by CO_2 capture from the atmosphere by tree growth.

4.5.2.2 Foundations and Infrastructure (F&I)

This family group is mostly composed of concrete-based products including bedding concrete, concrete shuttering blocks, precast reinforced concrete slabs, the exterior wall in reinforced concrete. It includes also waterproofing synthetic membrane. Their dynamic impact assessment is presented in Figure 4-21.

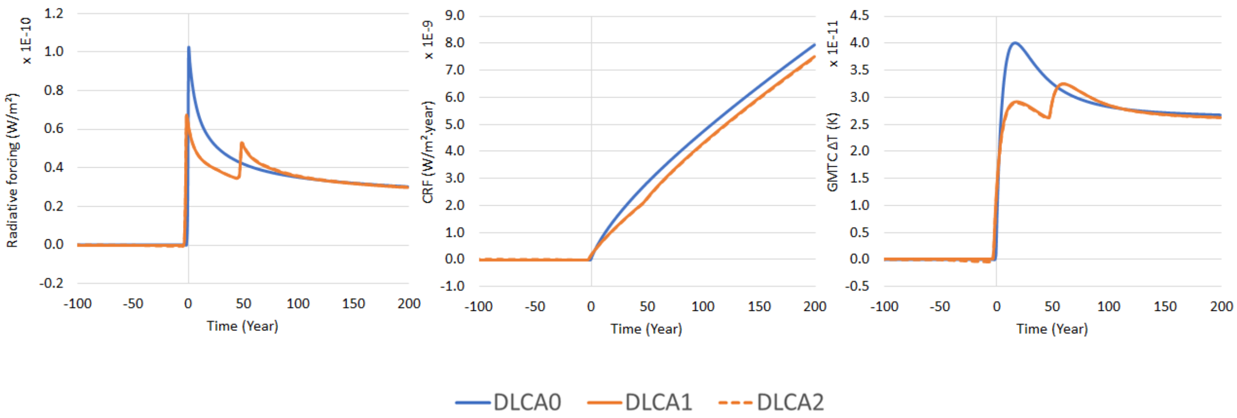


Figure 4-21: Comparison of DLCA results for F&I group following models DLCA0, DLCA1 and DLCA2

In this family group, there is no replacement of products during the building lifetime. Thus, only two distinct emission periods occurred, corresponding to the construction (the first pic of radiative forcing) and end-of-life (the second one) stages. Also, there is negligible biogenic CO2 involved, consequently models DLCA1 and 2 give similar results. The two peaks of temperature increase, thus, happen several years later than the emissions. DLCA0 model estimates slightly and constantly higher impact in terms of CRF than DLCA1 by 9% for almost all period of analysis, while more significant differences are observed for short term with respect to GMTC. The peak of GMTC for DLCA0 is of 4.0E-11 K at 12th year, while the two peaks of GMTC for DLCA1 and 2 correspond to 2.9E-11 K at 12th year and 3.3E-11 K at 60th year. However, these temperature peaks remain smaller than the overall GMTC of static emission model DLCA0. Looking at the 100th year, GMTC values calculated with the three models converge to the same level.

The fact of not presenting replacements during building lifecycle, allied to the fact that its end-of-life does not present a great impact, implies that the difference between static DLCA0 and dynamic DLCA1 are low.

The carbonation, a chemical process of CO_2 absorption by concrete products, was considered in LCI modelling (data provided by concrete fabricants). However, its influence on results is only marginal as the quantity of absorbed CO_2 is very low.

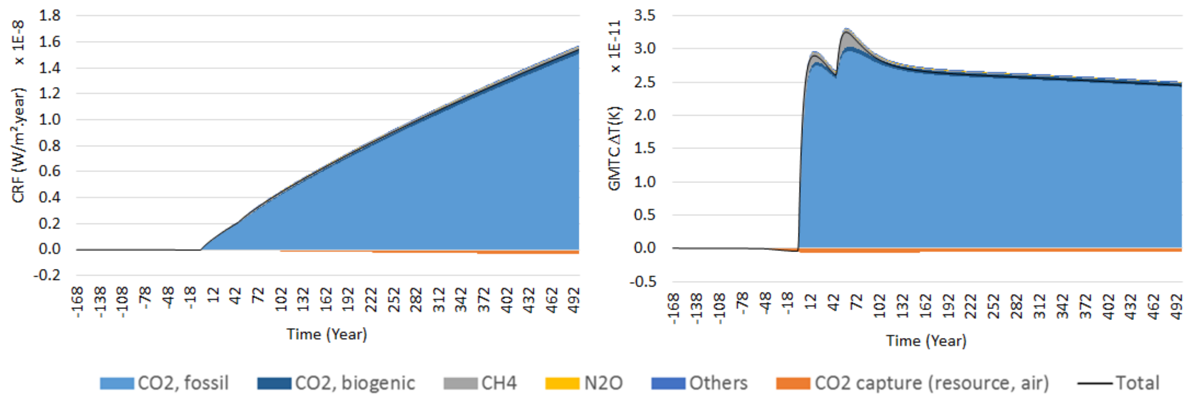


Figure 4-22: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for F&I group

As shown in Figure 4-22, CO_2 is almost completely responsible for the impacts both in short and long-terms. There is no wood-based product in this family group even though there may be some wood or vegetal product as raw material somewhere in the life cycle system. A very low-level impact of captured CO_2 can be observed here (orange area). This is the carbonation effect due to concrete products.

4.5.2.3 Superstructure and Masonry (S&M)

This product family is composed of the wooden floor, floating screed and mortar in concrete, the insulation material and the wall in timber frame. This group accounts for 19% of the total impact of construction products following the conventional LCA results.

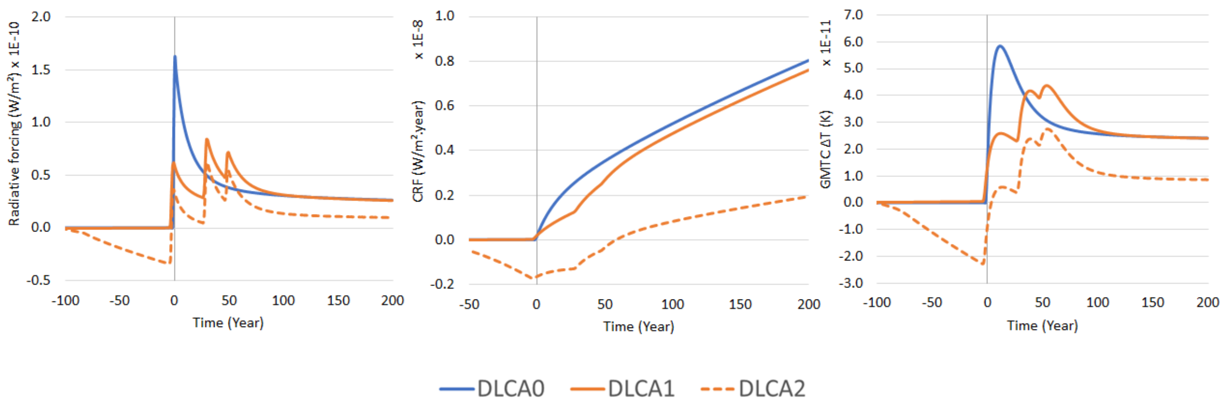


Figure 4-23: Comparison of DLCA results for S&M group following models DLCA0, DLCA1 and DLCA2

In Figure 4-23, we can observe important variations of LCA results between different DLCA models. The behavior of this group is similar to those of *H&MEW* group shown above. Temporal distribution of emissions in case of DLCA1 makes significant differences on the amplitude and the peak timing with respect to DLCA0. GMTC for DLCA0 attains the peak of 5.9E-11 K at the 10th year while DLCA1 presents three distinct peaks (2.5E-11 K at 6th year, 4.1E-11 K at 36th year and 4.4E-11 K at 55th year). The second one corresponds to the effect of the replacement of insulation materials that have a lifetime of 30 years.

When taking into account the effect of biogenic CO_2 in DLCA2 model, the temperature change attains its maximum of 3.8E-11 K at 55th year. The peak temperature of DLCA0 is almost twice than those of DLCA2, and there is a delay of 50 years between these peaks, due to the temporal distribution of emissions in dynamic models (DLCA1&2).

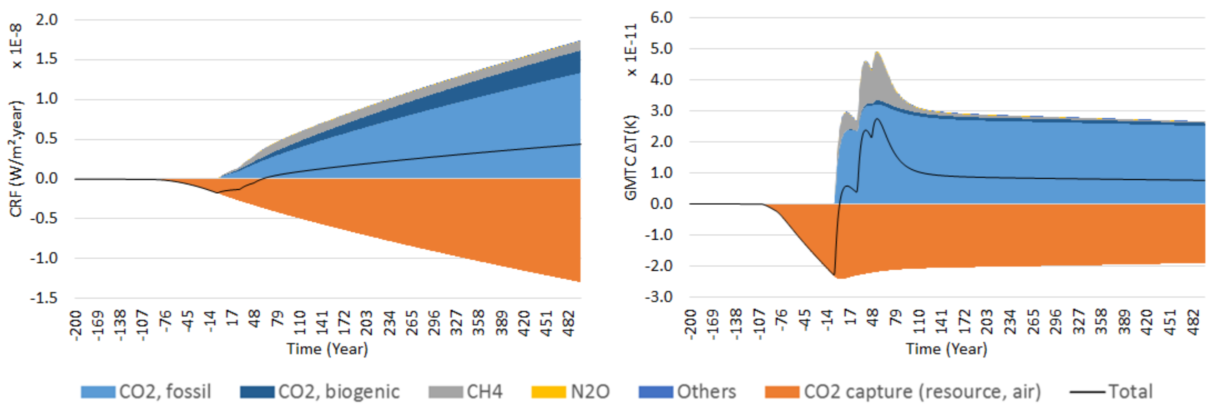


Figure 4-24: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for S&M group

This group uses much amount of wood-based materials, and Figure 4-24 shows that the effect of CO_2 uptake by trees can reduce until around 1/3 of temperature increase in the long term. This example also emphasizes the influence of CH_4 on the temperature increase in a short period. In addition, the results indicate that most of the temperature increase at the replacement phase (around 30th year) is due to CH_4 emissions. This end-of-life behaviour is observed for all product families in the following analysis.

Emitting principally CH_4 provokes a rapid increase of temperature in a short-term, but the reduction of temperature is also rapid due to a short residence time of CH_4 comparing to CO_2.

4.5.2.4 *Roofing, Tightness, Framework, Flashing (RTFF)*

This product family is composed of a metallic sheet for cladding, synthetic waterproofing membrane, and resinous frame. This group accounts for 13% of the total impact of construction products contributor with respect to conventional LCA.

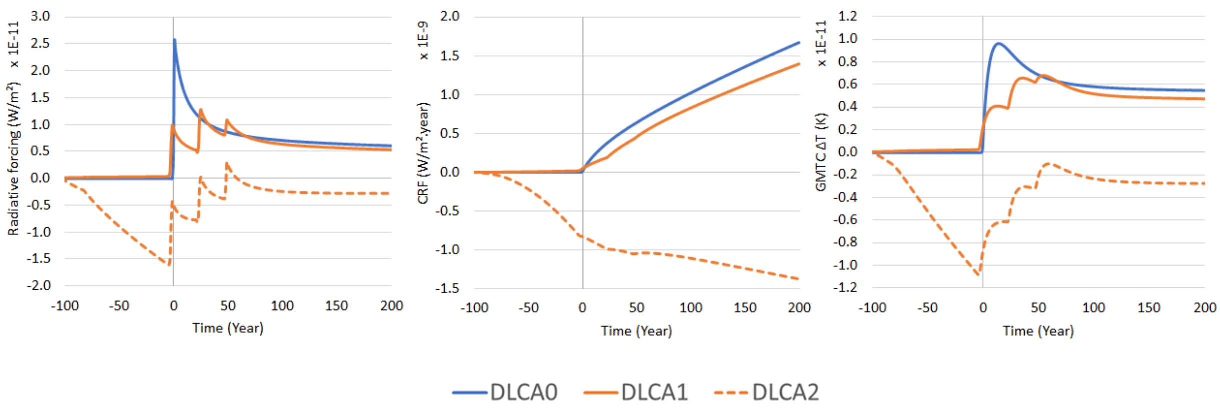


Figure 4-25: Comparison of DLCA results for RTFF group following models DLCA0, DLCA1, and DLCA2

At the right of Figure 4-25, we can observe three peaks of temperature change due to emissions occurring at the construction 0th, replacement at 25th, and the end-of-life at 50th years. The CRF at the 100th year of DLCA1 is 17% lower than DLCA0. The highest peak temperature in case of DLCA2 is placed at the 55th year with -6.8E-12 K. But the most important remark here is that the impact calculated with DLCA2 is negative, meaning that an environmental benefit can be obtained using this kind of construction materials (under the reserve of a sustainable end of life of these products).

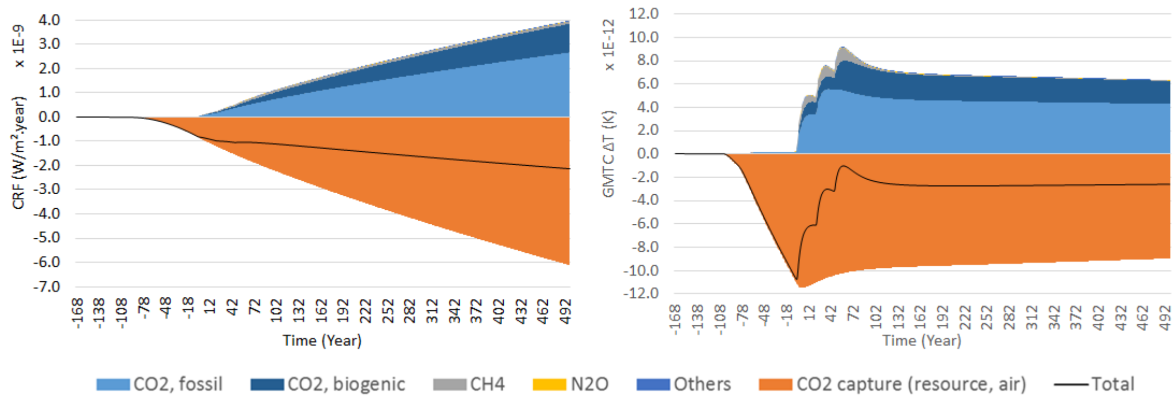


Figure 4-26: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) with DLCA2 model for RTFF group

Figure 4-26 shows the contribution of principal GHGs to climate change impacts, as obtained with DLCA2 model. Considering CO2 uptake by trees, the net impact becomes negative as the effect of GHG emissions is lower than the beneficial effect of CO_2 absorption. The presence of 300 m² of the resinous frame in this group significantly affects impact assessments due to the CO_2 absorption during a tree growth period in the past (100 years ago from the construction stage).

This example sheds light on the possibility to neutralize the effect of GHG emissions by a sufficient CO_2 capture, with appropriate timing of capture and emission processes.

4.5.2.5 *Partitioning, Lining, Suspended Ceiling, Interior Carpentry (P&IC)*

This family group is composed of doors, plasterboards, and suspended ceiling. There is a replacement of doors at 25^{th} year. This group accounts for 6 % of the total impact of construction products contributor with respect to conventional LCA.

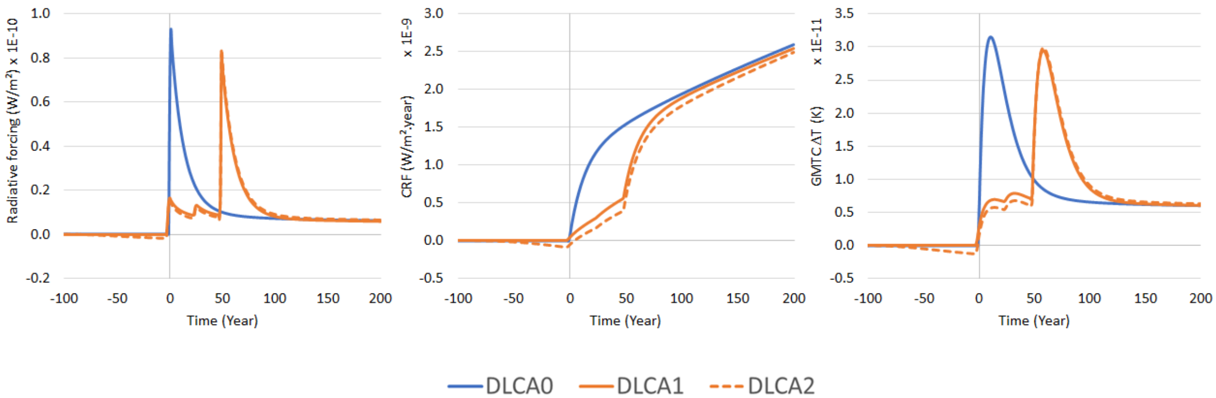


Figure 4-27: Comparison of DLCA results for P&IC group following models DLCA0, DLCA1, and DLCA2

Figure 4-27 shows that employing different LCA models one obtains different behaviors in short and long term impacts. While we observe slight increases of the impacts at time 0 and 25 that respectively correspond to the construction and door replacement phases, the impacts in this group are mostly related to the end-of-life phase. Thus, DLCA0 leads to an unrealistic timing of impacts. DLCA1 shifts almost totally the impacts later. For this family, there is no significant effect of biogenic CO_2.

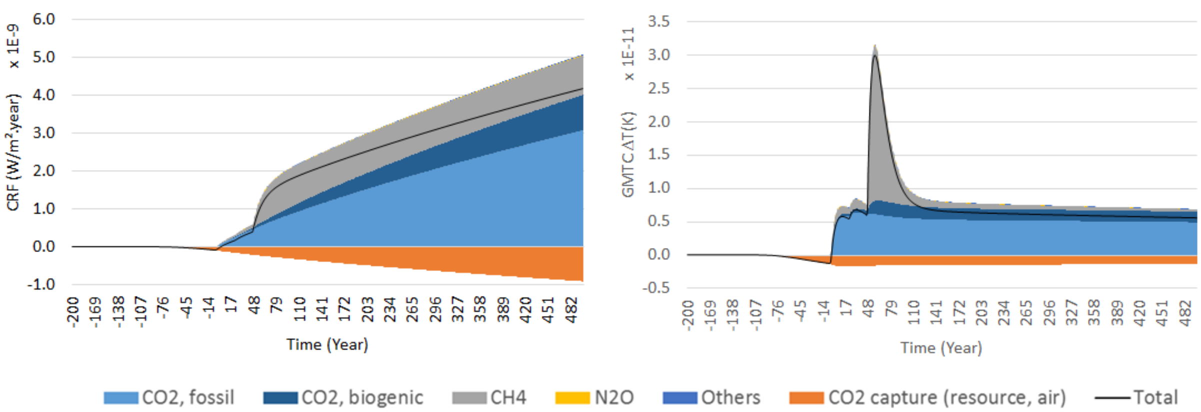


Figure 4-28: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for P&IC group

Figure 4-28 clearly distinguishes between a short-term and high impact due to CH_4 emissions and a long-term effect impact due to CO_2 emissions. In this specific case study, "plasterboard" used as interior partitioning is considered to be treated as waste in a sanitary landfilling center at its end of life. This process of landfilling emits CH_4. The waste treatment of "plasterboard" represents on its own 76% of CH_4 emissions of its total amount for this family group.

In case of such behaviors, mitigation decisions for climate change would aim at eliminating the sources of the sudden increase in temperature in the future.

4.5.2.6 *Façade and Exterior Carpentry (F&EC)*

This family group is composed of wood cladding, steel cladding, roller shutter in steel, and double glazing windows in PVC. Roller shutter and windows are replaced by new ones at 30th year. This group accounts for 6 % of the total impact of construction products following conventional LCA results.

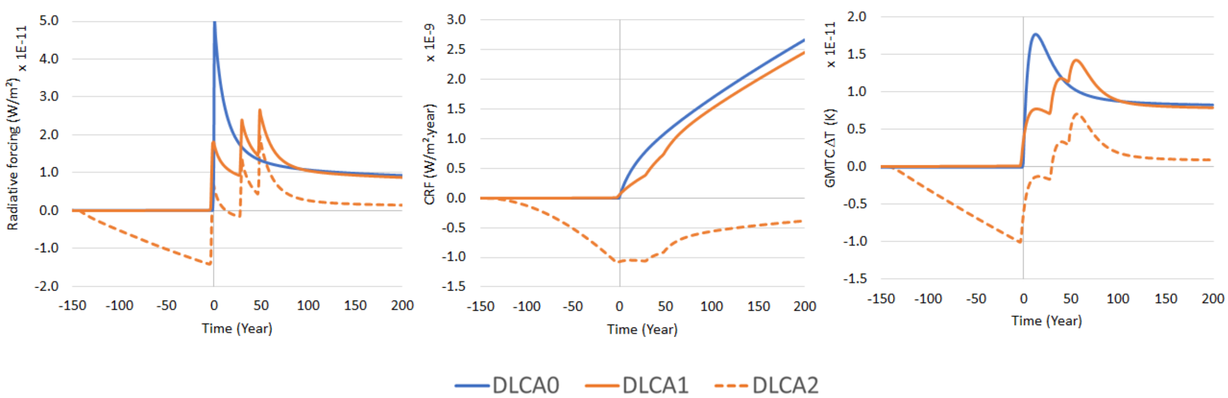


Figure 4-29: Comparison of DLCA results for F&EC group following models DLCA0, DLCA1, and DLCA2

Figure 4-29 shows important variations with respect to short-term impacts between DLCA models. Looking at the 100th year, CRF of DLCA0 is 12% higher than that of DLCA1. GMTC of DLCA0 attains a peak of 1.78E-11K, while GMTC with DLCA1 attains the highest peak of 1.45E-11K with a delay of 50 years. Then, the effect of accounting for biogenic CO_2 in DLCA2 makes lower net impacts, even of negative value. Although CRF is a negative value, GMTC becomes positive after a certain period when emissions of end of life stage occur. Therefore, the temperature change after several hundreds of years would possibly go through a negative value.

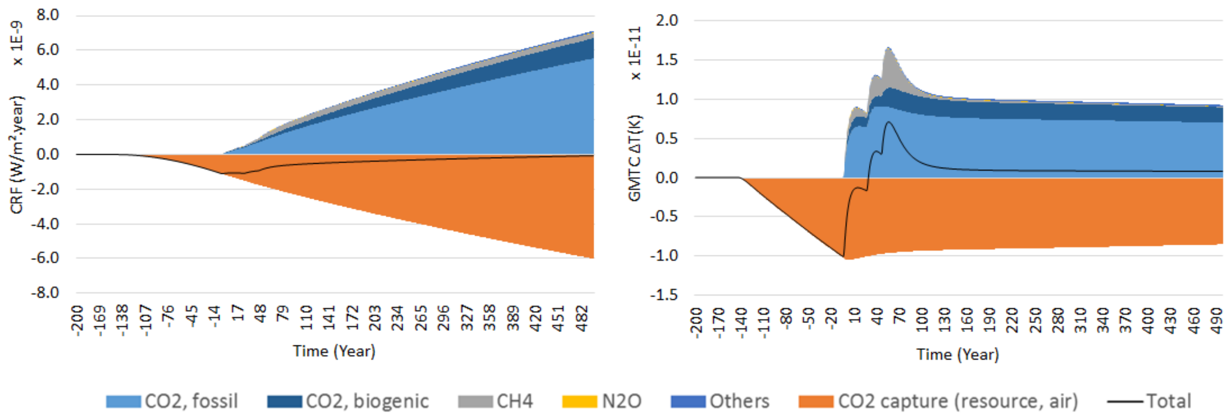


Figure 4-30: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for F&EC group

The result comparison in Figure 4-30 demonstrates that the neutrality of CO2 emissions is practically attained in a long-term since the effect of CO2 emissions from the construction to the end of life is counterbalanced by the effect of CO2 absorptions by the tree before the construction stage. Here, the mitigation efforts can be concentrated to diminish a temperature increase due to CH_4 emissions by waste treatment. The specificity of this example lies in the behavior of the dynamic indicators when GHG emissions and captures take place. A negative value of cumulated radiative forcing CRF indicator co-exists with a positive mean temperature change GMTC, advising of the distinct meaning of these indicators.

4.5.2.7 Coverings

This product family is composed of floating screed, PVC flooring in slabs, ceramic tiling, paintings, and stain wood. The paintings and the flooring have a service lifetime of 10 and 20 years, respectively; there are replacements periodically. This group accounts for 9 % of the total impact of construction products, calculated with conventional LCA.

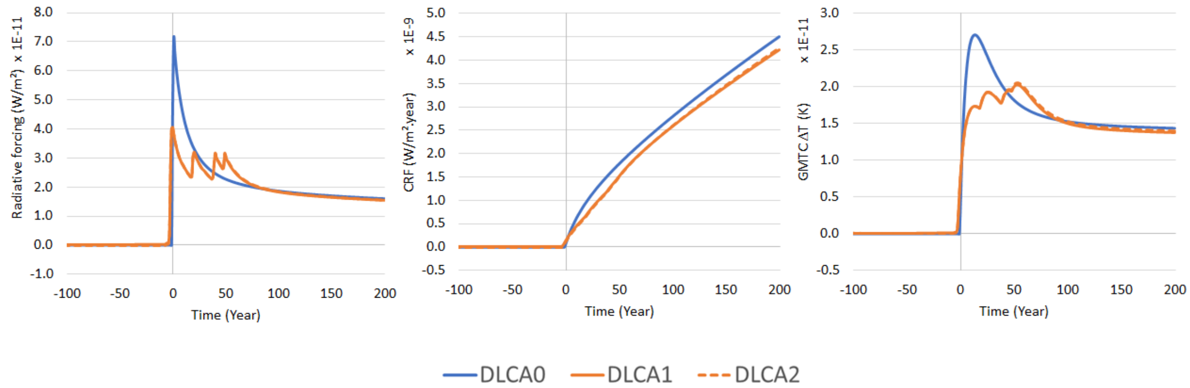


Figure 4-31: Comparison of DLCA results for Coverings group following models DLCA0, DLCA1, and DLCA2

Figure 4-31 shows, as for other family groups, that the replacement of products leads to delays of emissions, and in consequent delays of impacts. Looking at the 100th year, CRF resulted from DLCA0 is 8% higher than DLCA1 and the peak of GMTC for DLCA0 is 2.71E-11K at 12th year and 2.03E-11K at 52nd year for DLCA1, which is 25% lower than DLCA0. As there is no significant amount of wood-based products, an important variation does not exist between DLCA1 and DLCA2.

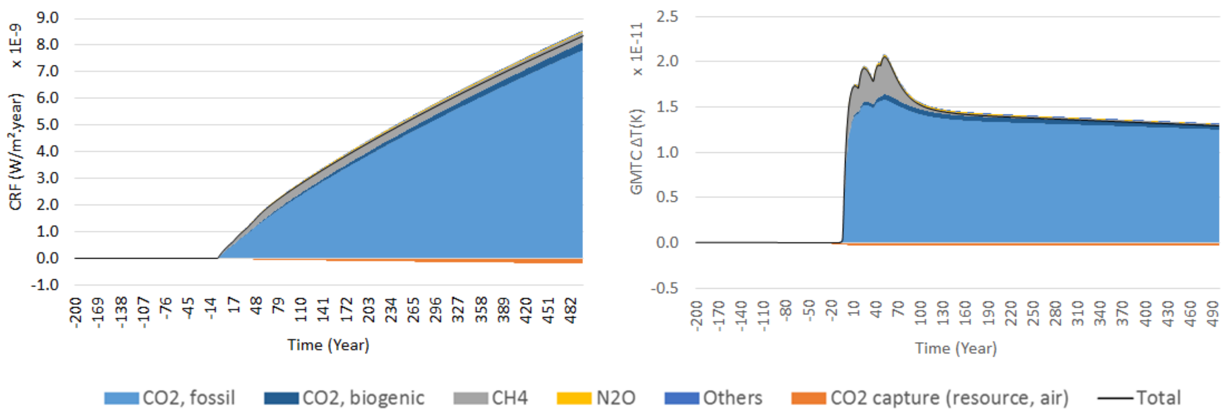


Figure 4-32: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for Coverings group

As shown in Figure 4-32, CO_2 dominates the impacts both in short and long-terms. The temperature change will remain high for a long period due to CO_2 concentration in the atmosphere. We also see a temperature increase due to the CH_4 emissions at replacement phases, but values remain relatively low compared to the effect of CO_2.

4.5.2.8 HVAC

This family group is composed of electric convector for the heating system and thermodynamic system for domestic sanitary hot water. This group represents the most important part among construction products with 19 % contribution to the impact of construction products contributor.

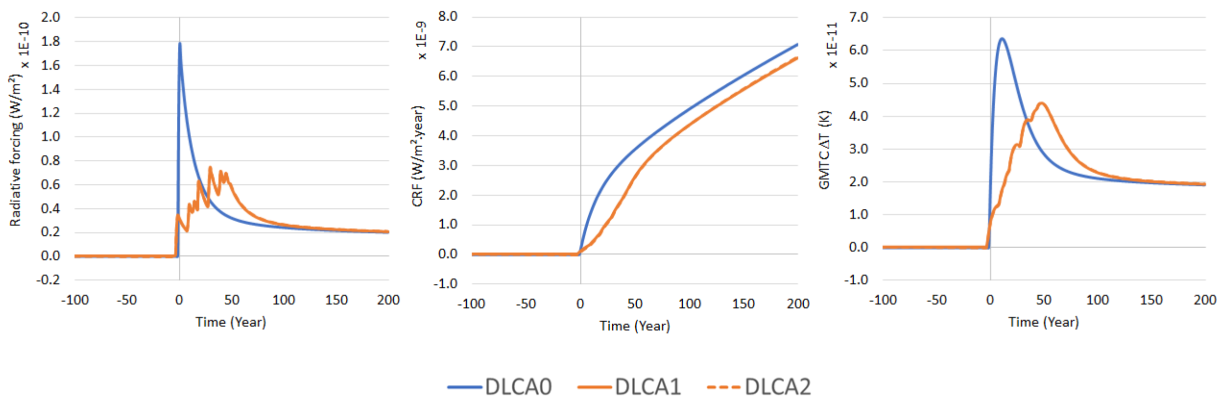


Figure 4-33: Comparison of DLCA results for HVAC group following models DLCA0, DLCA1, and DLCA2

This product family accounts for 16% of dynamic impact category CRF at the 100th year and 18% of GMTC also in the 100th year, with respect to the whole "construction products" contributor. HVAC equipment of the case study is composed of the heat pump, electric convector, and ventilation system. All of them are replaced during building lifetime (electric convector is replaced three times, the heat pump is replaced four times, and the ventilation system is replaced two times). These replacements can be noticed in Figure 4-33.

As there are no wood-based products in this family, there is no difference between DLCA1 and DLCA2 simulations.

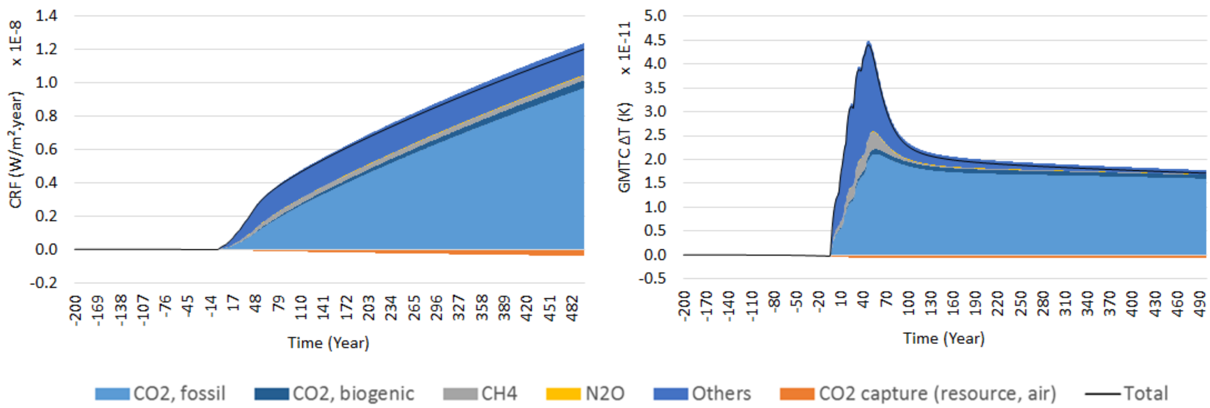


Figure 4-34: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for HVAC group

The result of composition analysis for this family group in Figure 4-34 demonstrates not only the effect of CO_2 in a long-term but also that the temperature peak is almost related to other GHG missions than CO_2, CH_4, and N_2O. This is a particular characteristic seen only for this group. HVAC systems, namely heating and cooling systems, dispose of the liquid circuit through which refrigerants known are used. These refrigerants are known for their environmental impacts, especially for global warming.

At the 52nd year when the temperature attains the peak of 4.4E-10K, HFC-134a (ethane, 1,1,1,2-tetrafluoro-) alone is responsible for 36% on its own, just after fossil CO_2 with 42%, due to its extremely high radiative efficiency (10 000 times higher than that of CO_2,). Only the ten most contributing GHGs make up to 98% of the total impact. In the long term, GMTC only depends on CO_2 concentration because CO_2 is 30 times more persistent than HFC-134a. The CRF indicator is by far dominated by fossil CO_2 due to its higher persistence in the atmosphere. The specific parameters of the main GHG and the relative contribution of the main GHG to the total GMTC at the 52nd year are respectively presented in Table 4-10 and Table 4-11.

Table 4-10: Specific radiative forcing and lifetime for substances considered in climate change impact (IPCC, 2013)

Compound	Specific radiative forcing (W/m^{-2}.ppb^{-1})	Lifetime (years)
Carbon dioxide	1.37E-05	3.94E+02
HFC-134a	1.60E-01	1.34E+01
Methane	3.63E-04	1.24E+01
Nitrous Oxide	3.00E-03	1.21E+01

Table 4-11: The 10 most contributing GHGs to global mean temperature change for the HVAC group

	Emission type	GMTC [K]	Contribution
1	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a(Air/high. pop.)	1.63E-11	36%
2	Carbon dioxide, fossil(Air/low. pop.)	8.39E-12	19%
3	Carbon dioxide, fossil(Air/high. pop.)	7.27E-12	16%
4	Carbon dioxide, fossil(Air/)	4.50E-12	10%
5	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113(Air/)	1.80E-12	4%
6	Methane, biogenic(Air/low. pop.)	1.76E-12	4%
7	Methane, fossil(Air/low. pop.)	1.19E-12	3%
8	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a(Air/)	1.18E-12	3%
9	Carbon dioxide, biogenic(Air/high. pop.)	7.04E-13	2%
10	Methane, fossil(Air/high. pop.)	6.39E-13	1%

Definitely, CO_2 is responsible for long term effects, far from the emission's end time, while other GHG can generate isolated, important temperature peaks.

4.5.2.9 Sanitary facilities (SF)

As there was no information of used materials for sanitary facilities, we took ourselves the hypothesis that the buildings are equiped of a kitchen, a bathroom, and toilettes. They all have the same service lifetime of 20 years, and toilettes are maintained every five years in this specific case study. This group only accounts for 3 % of the total impact of construction products contributor with respect to conventional LCA.

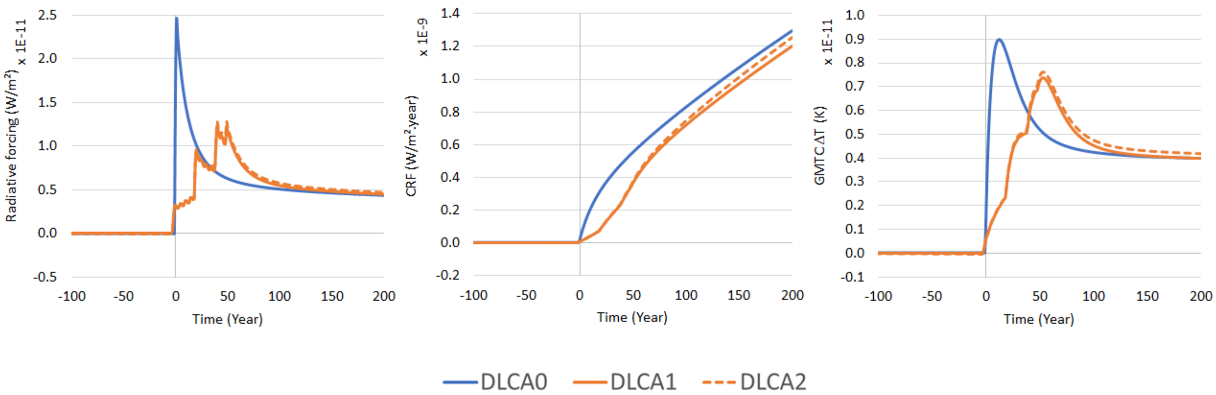


Figure 4-35: Comparison of DLCA results for SF group following models DLCA0, DLCA1, and DLCA2

Figure 4-35 shows that for CRF and GMTC, the values obtained with all the 3 models converge after about a hundred years. Looking at the 100th year, CRF of DLCA0 is 15% higher than DLCA1. Also, DLCA0 has a peak temperature of 8.98E-12K at 12th year, while DLCA1 has the peak of 7.36E-12K at 52th, and this one is 18% lower for DLCA1 than for DLCA0. As there is no wood-based product in this family, there is no significant difference between DLCA1 and DLCA2 results.

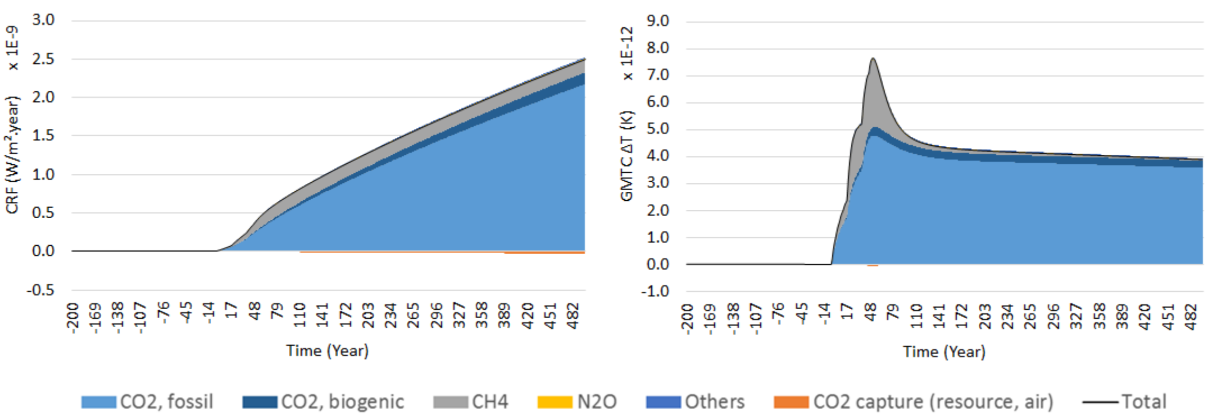


Figure 4-36: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for SF group

Figure 4-36 shows a long-term impact mostly related to CO_2 emissions and the peak temperature at 52nd year mostly related to CH_4 emissions. Analyzing the cause, we found out that this sudden increase in temperature is in particular due to CH_4 emissions. Materials used for "bathroom" and "toilettes" are considered to be treated as waste in a sanitary landfilling center at its end of life. This process of landfilling produces CH_4.

4.5.2.10 Energy networks (EN)

This family group represents materials for electrical cable and metal cabinet assigned to the buildings. Data assumption and LCI modeling were performed on the basis of literature reviews and generic LCI models built in the framework of MDEGD developed by CSTB (MEEM and MLHD, 2016). Electrical cables and metal cabinet have a service life of 30 and 20 years, respectively. This group only accounts for 4 % of the total impact of construction products contributor with respect to conventional LCA.

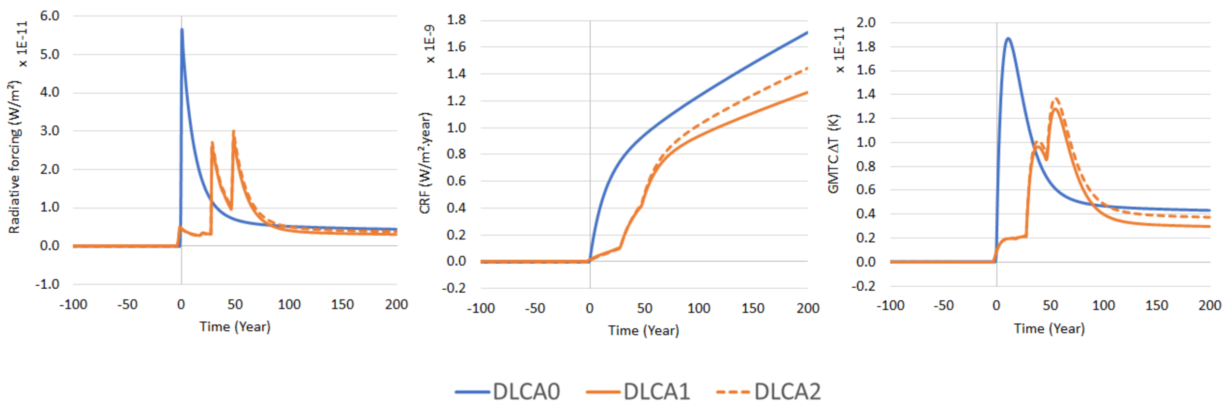


Figure 4-37: Comparison of DLCA results for EN group following models DLCA0, DLCA1, and DLCA2

In Figure 4-37, results of DLCA0 and DLCA1 present important variations for both CRF and GMTC indicators, and also for a short and long time horizon. Looking at the 100th year, CRF for DLCA0 is 32% higher than for DLCA1. Also, DLCA0 has a temperature peak of 4.49E-10K at 10th year, while DLCA1 has a peak of 1.28E-12K at 54th, being 31% lower than DLCA0. The peak temperature is postponed by 44 years.

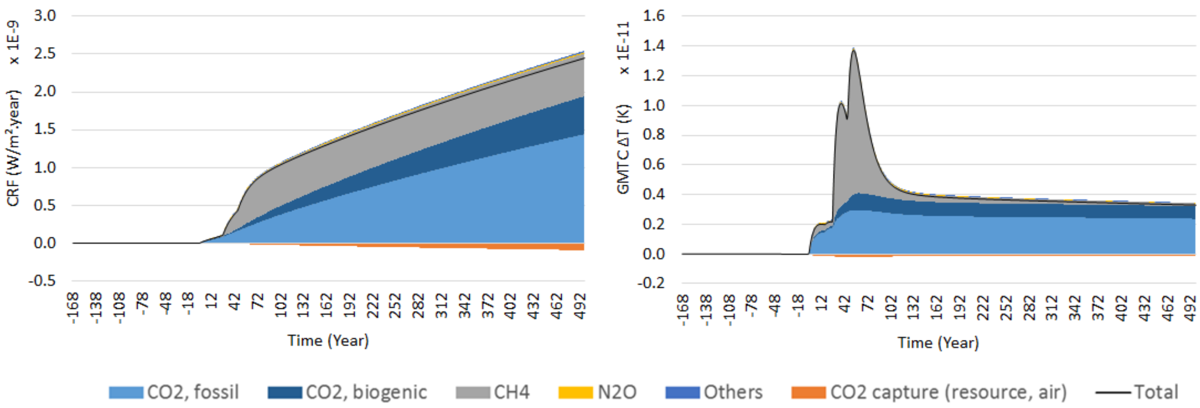


Figure 4-38: Contribution analysis of principal GHGs to climate change impacts (CRF (W//m²) at left and GMTC (K) at right) for energy networks group

Figure 4-38 clearly distinguish between a short-term impact due to CH_4 emissions and a long-term impact due to CO_2 emissions. In this family group, most of the used materials are considered to be treated as waste in a sanitary landfilling center at their end of life. This process of landfilling produces CH_4. For modelling this group, MDEGD processes are mostly used because there are no specific LCI models for this family group in the INIES data set. At this moment, MDEGD does not account for any scenario of valorization, and it always applies the same scenario of waste treatment when there is no other information (MEEM and MLHD, 2016). This is the reason why our study is based on 100% of landfilling scenario. This hypothesis should be discussed at the level of experts and is not addressed in this work.

4.5.3 Application to building scenarios

Scenarios of the same building are defined and assessed. The scenarios are obtained by changing several elements for which the time evolution can be foreseen. These elements are electricity mix, energy efficiency of the product manufacturing, technologies of end of life for concrete, steel and wood products, technologies for end of life of HVAC system, insulation materials, household energy consumption (with several sous-scenarios). In the following, the "baseline" scenario represents the building described and analyzed in Section 4.5.2. The "worst" represents a scenario expected to be less performant with respect to climate change impact, while "best" is one expected to be more favorable. However, their "best" or "worst" character will be determined by simulations.

Thus, the objectives of this section are to calculate the effect of different scenarios considered for the case study (presented in Table 4-7) and to evaluate the importance of prospective changes during the life time of the building. Also, we will compare conventional and dynamic LCA results in order to see if significant changes can be observed at the level of scenarios. This comparative analysis of different LCA metrics will provide elements for analyzing, in the next Chapter 5, for which scenario and for what type of studies (e.g., aiming at mitigation or adaptation? short or long term strategy?), the dynamic LCA approach is useful.

4.5.3.1 Electricity mix

The influence of the French electricity mix evolution on LCA results is analyzed here for conventional and dynamic LCA metrics. To remind, the baseline scenario uses the econivent process of electricity production "electricity, low voltage {FR}| market for" over the lifecycle of the building. The worst case (red bar in Figure 4-39) uses "Mix-50% Nuclear" scenarios for 2035-2050 and 2050-2065 periods. The best case (green bar) uses "Mix-90% RE&Gaz" scenarios for 2035-2050 and 2050-2065 periods (Table 4-12). These processes of the future mixes were developed as our specific ecoinvent processes (see Section 4.4.4). We remind that the background LCI data are retrieved from ecoinvent, considering that the technologies for electricity production are the same over the calculation period. The calculation period represents the use stage of the building, i.e., 50 years, from 2015 to 2065.

The climate change impacts from end-users energy consumption are calculated with these three scenarios.

Table 4-12: Scenarios of energy mix

Baseline scenario	Worst case scenario	Best case scenario
French annual average mix using ecoinvent data “electricity, low voltage {FR}| market for” Period 2015-2065 years (entire use stage of the building)	French annual average mix using ecoinvent data “electricity, low voltage {FR}| market for” for 2015-2034	French annual average mix using ecoinvent data “electricity, low voltage {FR}| market for” for 2015-2034
	“Mix-50% Nuclear” scenarios for 2035-2050	“Mix-90% RE&Gaz” scenarios for 2035-2050
	“Mix-50% Nuclear” scenarios for 2050-2065	“Mix-90% RE&Gaz” scenarios for 2050-2065

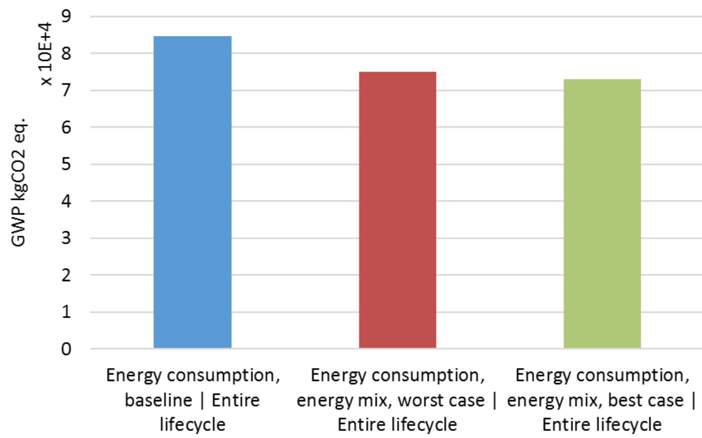


Figure 4-39: Scenario analysis of the energy mix for the climate change impact with the conventional LCA method (GWP100)

In Figure 4-39 are presented the conventional LCA results for GWP100 (following EN15804). The worst case scenario has 11.5% impact reduction and 13.8% in the case of the best case scenario. Even though energy mix composition will be radically evolved by replacing nuclear power by other renewable energies, the impact does not change dramatically. This fact can be explained by the fact that nuclear power already produces a very low carbon footprint energy (current inventory dataset in ecoinvent), and replacing it by renewable systems does not significantly modify this performance.

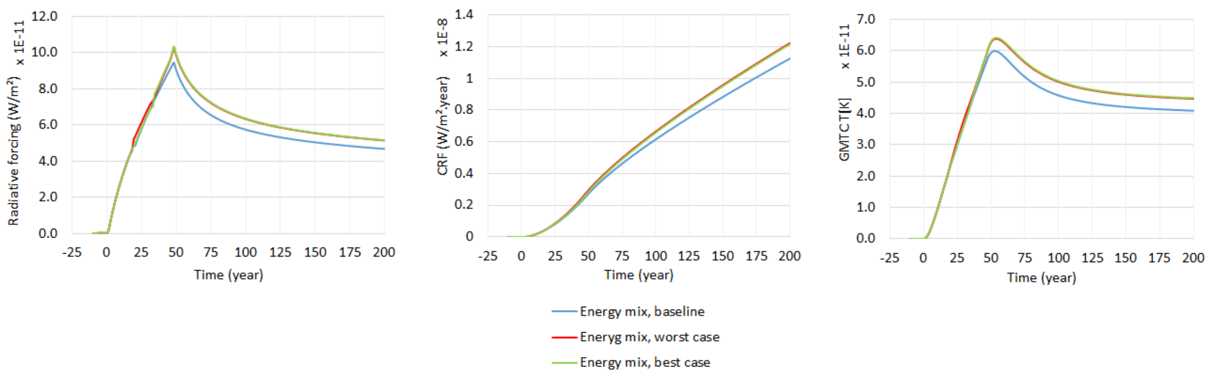


Figure 4-40: Scenario analysis of the energy mix for the climate change impact with the dynamic LCA method

In Figure 4-40, the same energy consumption model (50 years - energy consumption in the building's use phase) with three mix scenarios are evaluated over 200 years using the dynamic LCA method. There is no clear difference between the two new scenarios. However, conversely to the conventional LCA results, dynamic LCA gives slightly higher impact for the future production mixes compared to the baseline scenario. Global mean temperature change attains its peak at about 55th year. At 100 years, the worst and best case scenarios give both 7% higher impacts than baseline scenario for CRF, and 10% higher for GMTC.

Table 4-13 resumes the value of CRF and GMTC at 55th, 100th and 150th year and the conventional LCA values with a time horizon of 100 years. In the same table, are presented in parenthesis relative differences of impacts regarding the baseline scenario.

Table 4-13: Comparison of climate change impacts between different LCA metrics for three time horizons (55, 100 and 150 years for dynamic LCA)

Scenario name	**GWP 100**	**CRF (W/m².Year)**			**GMTC (K)**		
	(kg CO2 eq.)	**55th Year**	**100th Year**	**150th Year**	**55th Year**	**100th Year**	**150th Year**
Baseline	**84671**	3.25E-09	**6.20E-09**	8.86E-09	5.96E-11	**4.57E-11**	4.20E-11
Worst case	**74914**	3.41E-09	**6.65E-09**	9.59E-09	6.39E-11	**5.03E-11**	4.61E-11
	(-11.5%)	(+5%)	**(+7%)**	(+8%)	(+7%)	**(+10%)**	(+10%)
Best Case	**73002**	3.38E-09	**6.62E-09**	9.56E-09	6.40E-11	**5.03E-11**	4.62E-11
	(-13.8%)	(+4%)	**(+7%)**	(+8%)	(+7%)	**(+10%)**	(+10%)

When analyzing the benefit of future production mix in the frame of our case study, the ranking is inversed between conventional and dynamic LCA. The reason for this result is explained by the different ways of considering biogenic CO_2 in the two methods. In both "best" and "worst" scenario, the contribution of bio-based resources to the French power grid tends to increase over the years. Therefore, CO_2 uptake by the plant and its release when generating energy disturbs the atmospheric CO_2 balance during the concerned period (the building's use phase). The dynamics of biogenic CO_2 is correctly considered in DLCA, while it is missing in conventional LCA which provides a wrong ranking.

4.5.3.2 Energy efficiency at product manufacturing

The influence on LCA results of the scenario of energy efficiency improvement at product manufacturing is analyzed here for conventional and dynamic LCA metrics. To remind, the baseline scenario uses raw ecoinvent processes, and the best case uses the created processes to which a 10% reduction of energy consumption every decade at product fabrication processes as shown in Table 4-14. The calculation was performed for all concrete, steel and wood products, with the baseline electricity mix.

Table 4-14: Scenario of energy efficiency at product manicuring

Baseline scenario	**Worst case scenario**	**Best case scenario**
No temporal variation of energy consumption using raw ecoinvent data	No worst case scenario is set	10% reduction of energy consumption per decade at concrete, steel, aluminum and wood product manufacturing processes

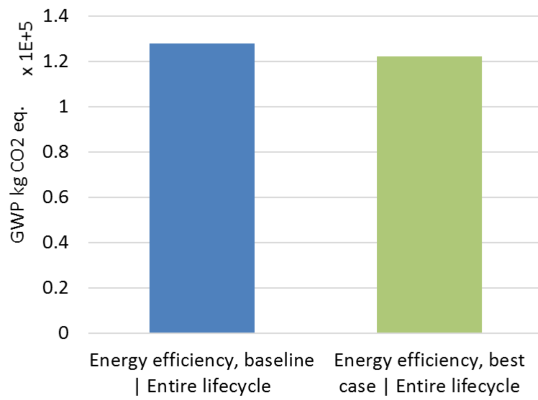


Figure 4-41: Scenario analysis of the energy efficiency at the phase of product fabrications (concrete, steel and wood products) for the climate change impact with the conventional LCA method (GWP100)

In Figure 4-41, is presented the comparison between the 2 scenarios for energy consumption at the products fabrication phase, on the basis of conventional indicator GWP100. "Best case" represents an improvement of energy efficiency by 10% for every decade for the fabrication of the products. Only 4% of the total impacts (kg CO_2 eq) was gained thanks to this prospective scenario.

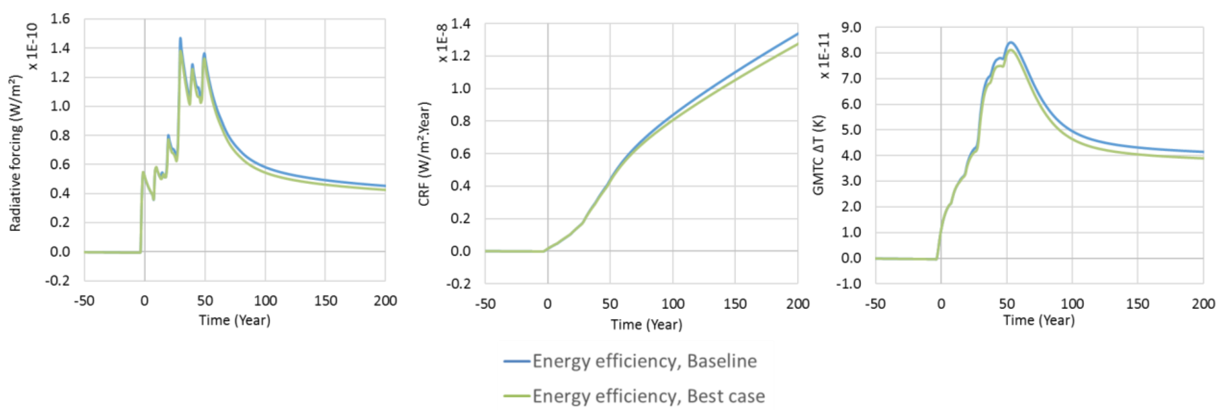


Figure 4-42: Analysis of the energy efficiency at the phase of products fabrication, for the climate change impact with the dynamic LCA method

In Figure 4-42, the same LCI model of two scenarios of energy consumption during the fabrication of the products (actual energy efficiency and prospective energy efficiency) is evaluated over 200 years, using the dynamic LCA method. As can be seen in the conventional LCA result, the impacts for the two scenarios are not significantly different. Looking at the 100th year, the best case scenario does not have an important impact on LCA results with 3% and 4% reductions, respectively for CRF and GMTC. As this testbed building is principally based on wood products, it would be interesting to study how LCA results can change if we apply the scenario of energy efficiency to other types of buildings (e.g., concrete).

4.5.3.3 The technology of end-of-life scenario of concrete, steel and wood products

The influence of the end-of-life technologies for concrete, steel, and wood products on LCA results is analyzed here for conventional and dynamic LCA metrics. To remind, the baseline scenarios are retrieved from EPDs combining landfill, incineration, and recycling as waste treatment processes. The "worst" case scenario is when the end-of-life of one material type is only "landfill," and the "best" case scenario is that for which the recycling rate is increased with respect to EPDs' baseline. However, we don't know a priori which the best solution is, and that is what we analyze in the following.

For this analysis, we calculated the impacts from construction products through A1 to C4 stages for each type of materials (concrete, steel, and wood) present in the building, by considering the variation of waste treatment scenario (landfill, incineration, or recycling at C4 stage). The functional unit for this scenario analysis remains the three single attached houses for 50 years (described in Section 4.2), and thus, the reference flow for each type of three materials is calculated with respect to the functional unit. Table 4-15 resumes the scenarios considered. Construction products concerned for this scenario analysis are synthetized in Annex III.

Table 4-15: Scenarios of end-of-life technologies for concrete, steel, and wood products

Baseline scenario	Worst case scenario	Best case scenario
EPDs processes (landfill, incineration, recycling)	Landfill for all products	Increase in recycling rate with respect to EPDs

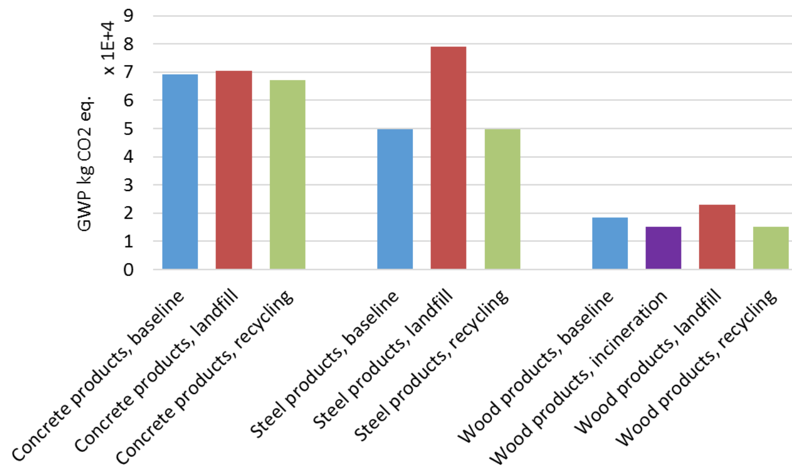
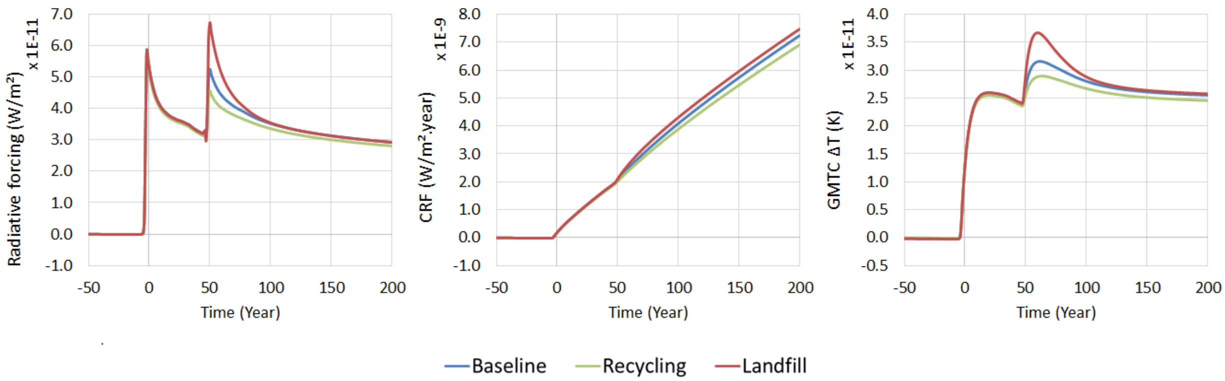


Figure 4-43: Scenario analysis of concrete, steel and wood products for climate change impact with conventional LCA method (GWP100), for 3 end of life technologies

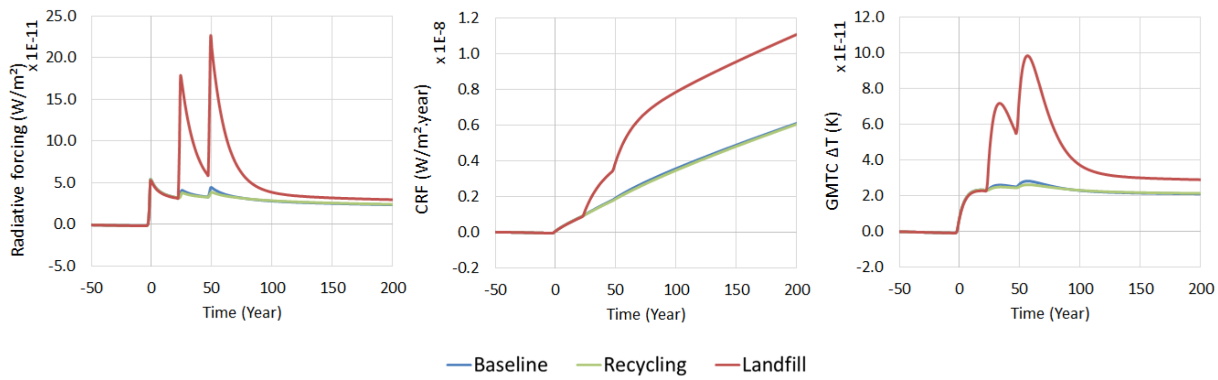
Figure 4-43 presents the comparison of the different scenarios of the waste treatment of concrete, steel, and wood products on the basis of a conventional indicator GWP100 (following EN15804 method, without biogenic CO_2). The graph shows that the landfill scenario (worst case) of steel products has a significant impact. Meanwhile, recycling scenarios do not change results too much. Wood products with incineration scenario have a smaller impact than all the other types of treatment processes.

Figure 4-44 shows the dynamic profiles of the climate change impacts for concrete, steel, and wood products with different end-of-life technologies.

Concrete products



Steel products



Wood products

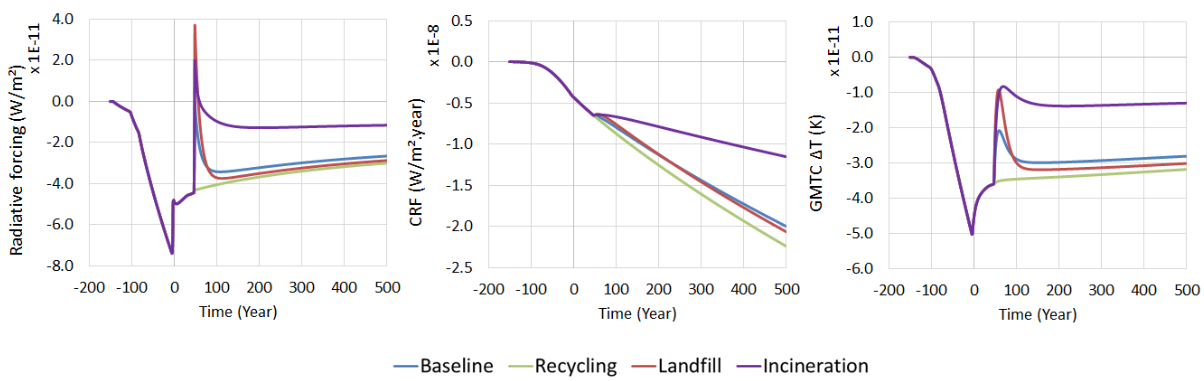


Figure 4-44: Scenario analysis of concrete, steel, and wood products for climate change impacts with dynamic LCA method (top: concrete products, middle: steel products, bottom: wood products), with different end of life technologies

For *concrete products* (graphs at the top), one observes the same ranking of scenarios with respect to the results obtained with conventional LCA. However, the dynamic indicators accentuate the differences between the compared scenarios, while conventional LCA (Figure 4-43) shows only slight differences. With dynamic LCA, the temperature peak is placed around the 55^{th} year for all scenarios, and the most impacting scenario is landfilling with the peak of 3.63E-11 K, which is 16% higher than the baseline scenario. However, the temperature rapidly falls on the same level as the baseline scenario at the 100^{th} year.

For *steel products* (graphs at the middle), dynamic LCA gives CRF of 7.90E-09 W/m².year at 100 years for the landfilling scenario, which is almost twice the baseline CRF. Also, GMTC impact for landfilling is 60% higher than for the baseline scenario. Regarding the GMTC impact for the steel products, two temperatures peaks appear around 35 (+180% of the baseline) and 55 years (+250% of the baseline). All dynamic indicators give landfill as the worst scenario, while baseline and recycling are similar. This feature is akin to conclusions from conventional LCA.

In the bottom figure for *wood products*, the incineration scenario for wooden wastes has higher impacts than the other scenarios because of the consideration of biogenic CO_2 effect. However, when considering CO_2 uptake for tree growth, the overall impacts (from the beginning of tree growth to the end of life) have net negative values for CRF and GMTC indicators, and negative RF except for the emission moment, i.e., at the end of a life time (for incineration and landfill). Besides, comparing the GMTC indicator between baseline and landfill, it is found that the impact ranking is inversed between in short and long time scale. Landfill contributes much to the increase in the atmospheric concentration of methane, but, the temperature rapidly declines due to the short lifetime of methane. Meanwhile, the baseline scenario takes the mix of incineration, landfill, and recycling, with a lower methane quantity, thus a smaller peak, and a higher impact at long term than landfill scenario.

When comparing the 3 material groups, dynamic indicators clearly discriminate wood products from the 2 others. While conventional LCA calculates significant GWP impact, dynamic indicators show that carbon capture effect can neutralize and even overtake GHG emission effects.

4.5.3.4 Technology of end-of-life scenario of HVAC system

Similarly to the previous scenario analysis, the influence of the end-of-life technologies for HVAC system on LCA results is analyzed here with both conventional and dynamic LCA metrics. The baseline scenario is retrieved from EPDs combining landfill and recycling as treatment technologies. The worst case scenario is when the end-of-life processes are set as “landfill,” and the best case scenario is when we consider the increase in recycling rate with respect to EPDs’ baseline (Table 4-16).

Table 4-16: Scenarios of end-of-life technologies of the HVAC system

Baseline scenario	Worst case scenario	Best case scenario
EPDs processes (landfill, recycling)	Landfill for all products	Increase in recycling rate with respect to EPDs processes

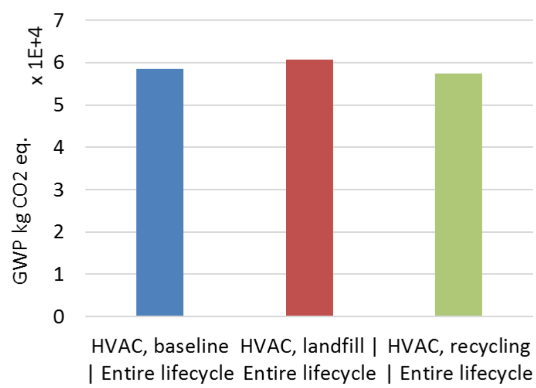


Figure 4-45: Scenario analysis of HVAC systems for climate change impact with conventional LCA method (GWP100), with 3 end of life technologies

Figure 4-45 shows the comparison of the conventional impact (GWP100) between three scenarios of end-of-life technologies. Impacts do not much vary from a scenario to another.

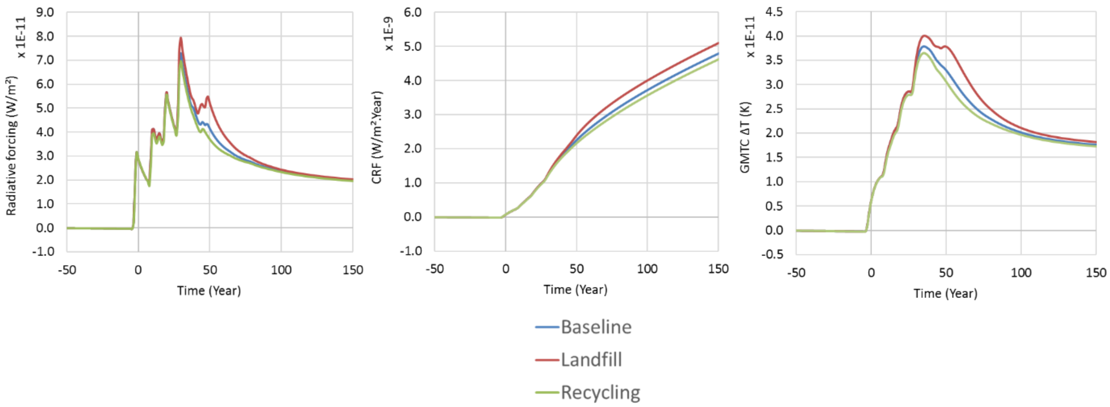


Figure 4-46: Scenario analysis of HVAC systems for climate change impacts with dynamic LCA method, for 3 end of life technologies

In Figure 4-46, small variations of dynamic impacts are observed between the three scenarios (with a slightly higher impact for landfilling), which is akin to conventional LCA results.

4.5.3.5 Technological innovations of insulation materials

The insulation materials are rock wool, glass wool, and polyurethane. In the baseline scenario (ELODIE and EPDs) the material is replaced with the same one after 30 years. The worst case scenario is when insulation materials are 100% replaced by extruded polystyrene at the 30th year. For the best scenario, two innovative products are considered: one is the bio-based insulation material, and the other is composed of recycled materials. Table 4-17 resumes the scenarios considered.

Table 4-17: Scenarios of technological innovations of insulation materials

Baseline scenario	Worst case scenario	Best case scenarios
Replacement (30th year) of insulation materials by the same type as initially used.	Replacement (30th year) of all insulation materials by extruded polystyrene	1. Replacement (30th year) of all insulation materials by bio-based material 2. Replacement (30th year) of all insulation materials by one composed of recycled material

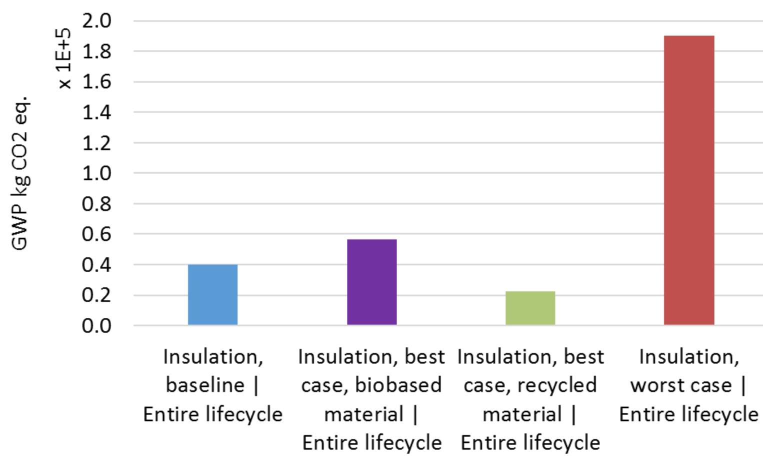


Figure 4-47: Scenario analysis for insulations materials following the conventional LCA method (GWP100)

Figure 4-47 shows that only insulation material based on recycled materials is better ranked than the baseline scenario. The worst case scenario has 378% higher impact than the baseline. Also, the bio-based insulation material is supposed to have less impact than the baseline due to the biogenic CO_2 effect. However, conventional LCA does not account for this effect.

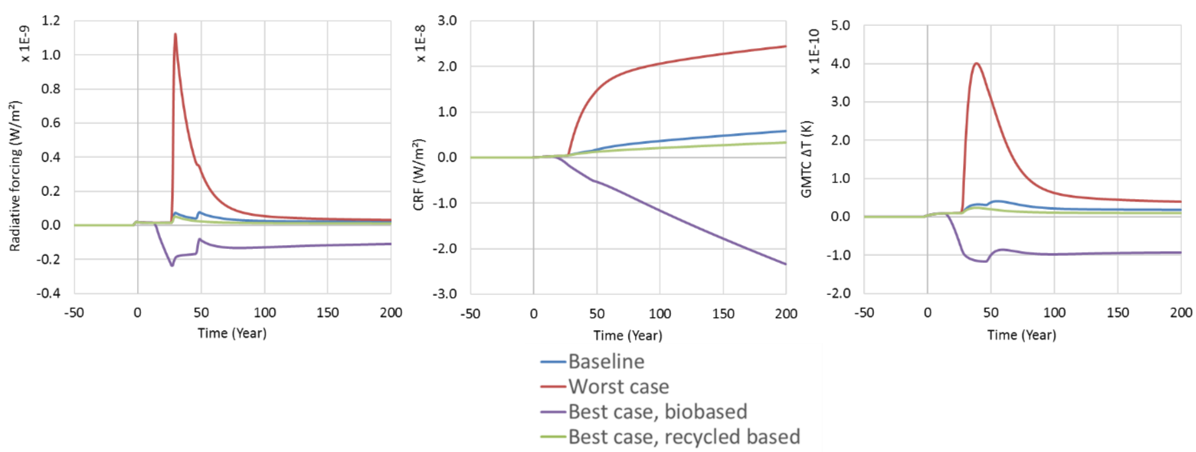


Figure 4-48: Scenario analysis of insulation materials for the climate change impacts with dynamic LCA method

Some important features of the dynamic metrics are revealed in Figure 4-48. First, the ranking of scenarios obtained with conventional LCA (Figure 4-47) is changed due to biogenic CO_2 effect considered in dynamic LCA. The bio-based scenario has net negative impacts, for all indicators, the use of bio-based insulation materials is thus benefic from the point of view of climate change impact. A second feature to be mentioned concerns the GMTC indicator at different time horizons. When considering the worst insulation material, the temperature attains 4.0E-10 K at the 35th year that is 875% higher than the temperature peak of the baseline. However, when looking at the temporal behavior of GMTC for a longer time horizon, the temperature declines before the 100th year and is only twice the baseline GMTC in the same year. This rapid variation of the dynamic indicators is due to the use of extruded polystyrene as insulation material and the emission of HFC-134a. When analyzing GMTC for the worst case (red), it is found that the contribution of HFC-134a to the peak temperature at the 39th year attained 80%. Extruded polystyrene has a high thermal performance, however, also presents a high contribution rate to global warming due to the use of HFC-134a for foam processing. According to the IPCC report, the effect of unitary emission of the HFC-134a for 100 years is 1430 times higher than CO_2 (Myhre et al., 2013).

4.5.3.6 Household energy consumption

The influence of the household energy consumption with different time variable parameters is analyzed here with conventional and dynamic LCA metrics. These variable parameters were used to perform dynamic energy simulation. To remind, the baseline does not consider the temporal evolution of any parameter. Table 4-18 gathers the scenarios with different parameter behavior. End-user's energy consumption during the building use phase is calculated, and the relative difference between energy consumptions with respect to the baseline scenario is evaluated in %. The scenarios 1 to 7 consider one variable parameter per scenario, while scenario 8 takes into account the combination of the all worst cases and inhabitant change (i.e., the number 3, 4, 6 and 7 are included at the same time).

Table 4-18: Comparison of sub-scenarios of household energy consumption over 50 years

	Sub-scenarios	kWh	Δ/Baseline
1	Baseline	7.34E+5	-
2	Heat Pump, COP, 1%/year ↓ (Best case)	7.47E+5	+2%
3	Heat Pump, COP, 3%/year ↓ (Worst case)	7.74E+5	+5%
4	Airtightness, 1%/year ↓ (Worst case)	7.61E+5	+4%
5	Insulation, thermal conductivity, 1%/year ↓ (Best case)	7.58E+5	+3%
6	Insulation, thermal conductivity, nonlinear degradation (Worst case)	8.13E+5	+11%
7	Inhabitants change, 5 pers./house => 2 pers./house in 2035	7.59E+5	+3%
8	Worst case combination - with inhabitant change	1.01E+6	+37%

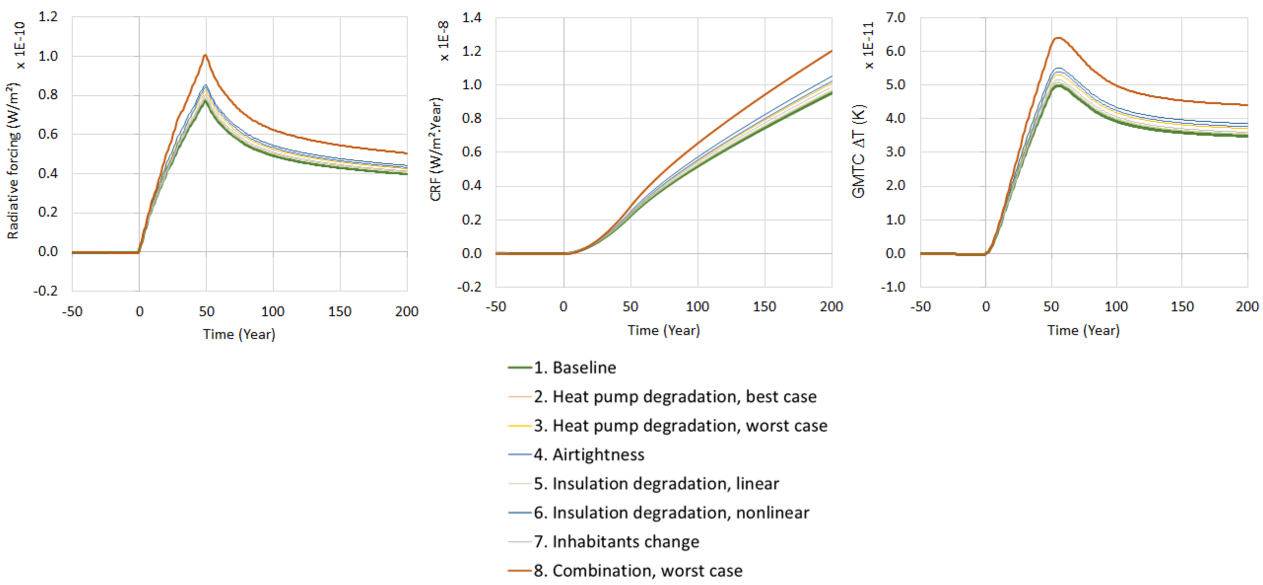


Figure 4-49: Analysis of sub-scenarios of household energy consumption for climate change impacts with dynamic LCA method

Calculations were performed with the baseline electricity mix. Figure 4-49 illustrates the possible variation of the climate change impacts of household energy consumption due to different scenarios (2 to 8), simulated with dynamic LCA method. The GMTC indicator of the combination scenario (Scenario 8, dark orange) attains the highest peak of 6.36E-11 K at the 55th year. This value is 28% higher than the baseline's peak of 4.98E-11 K (Scenario 1, dark green). Table 4-19 resumes the value of CRF and GMTC at 55th, 100th and 150th year and the conventional LCA values with a time horizon of 100 years. In the same table, are presented in parenthesis relative differences of impacts for each scenario regarding the baseline scenario. The relative differences for GWP are identical with those of energy consumption for different scenarios in Table 4-18, which was an expected result (all other parameters being constant). For most of the scenarios, the relative differences (scenario X versus baseline scenario) do not vary between conventional and dynamic LCA methods. Only for the combination scenario 8, it is found that the impact with dynamic LCA metrics has smaller relative differences comparing to that obtained by conventional LCA (in italic). Concerning the relative differences obtained with conventional and dynamic methods, in case of scenarios where only one parameter was modified, the differences are so small that a dynamic approach is not very useful for discriminating such scenario. In contrast, the effect of time lags of emissions is visible in scenario 8 for which the relative differences are significant. This scenario accumulates different types of system degradation, therefore, the energy consumptions vary at a long time scale. Consequently, the impacts of later emissions will appear later in time. This is the reason why the CRF indicator for the scenario 8 increases more significantly at each time horizon than other 6 scenarios.

Table 4-19: Comparison of climate change impacts of household energy consumption between different LCA metrics for three time horizons (55, 100 and 150 years for dynamic LCA)

Scenario	GWP 100 (kg CO2 eq.)	CRF (W/m².year)			GMTC ΔT (K)		
		55th year	100th year	150th year	55th year	100th year	150th year
1	84672	2.69E-09	5.23E-09	7.51E-09	4.98E-11	3.91E-11	3.59E-11
2	86099 (+2%)	2.74E-09 (+2%)	5.33E-09 (+2%)	7.66E-09 (+2%)	5.08E-11 (+2%)	3.99E-11 (+2%)	3.66E-11 (+2%)
3	89193 (+5%)	2.86E-09 (+6%)	5.57E-09 (+6%)	7.99E-09 (+6%)	5.31E-11 (+7%)	4.17E-11 (+7%)	3.82E-11 (+7%)
4	87731 (+4%)	2.86E-09 (+6%)	5.61E-09 (+7%)	8.08E-09 (+8%)	5.40E-11 (+8%)	4.24E-11 (+8%)	3.87E-11 (+8%)
5	87354 (+3%)	2.73E-09 (+1%)	5.31E-09 (+1%)	7.62E-09 (+2%)	5.06E-11 (+2%)	3.97E-11 (+2%)	3.64E-11 (+2%)
6	93768 (+11%)	2.97E-09 (+10%)	5.79E-09 (+11%)	8.30E-09 (+11%)	5.52E-11 (+11%)	4.33E-11 (+11%)	3.97E-11 (+11%)
7	87521 (+3%)	2.54E-09 (-6%)	5.24E-09 (+0%)	7.61E-09 (+1%)	5.13E-11 (+3%)	4.09E-11 (+5%)	3.72E-11 (+4%)
8	*116161 (+37%)*	*3.09E-09 (+15%)*	*6.43E-09 (+23%)*	*9.34E-09 (+24%)*	*6.36E-11 (+28%)*	*5.03E-11 (+29%)*	*4.55E-11 (+27%)*

4.6 Conclusion

This chapter presents the application of the dynamic LCA methodology to buildings through a case study. Climate change impact was evaluated with conventional and dynamic LCA approaches, and results were compared.

Two main objectives were pursuit: i) the feasibility of a dynamic LCA for buildings by using and adapting existent tools; ii) deepening our understanding about environmental impacts by comparing conventional

LCA results to dynamic results in order to see how result interpretation changes between different metrics for climate change impact (conventional GWP and three dynamic climate change indicators).

A testbed building was modeled in the framework of dynamic LCA approach by combining building data for dynamic LCI modelling and dynamic LCIA method for climate change impact. To realize dynamic LCI modelling, some features of DyPLCA tool were adapted because some processes in this case study do not follow the same general definition of temporal parameters for process and supply chain dynamics in DyPLCA model. The feasibility of the approach was thus demonstrated. Concerning the methodology application, the limiting factor is the calculation time with DyPLCA tool when many scenarios of technology change are considered together on the time scale (e.g., manifold changing of the electricity mix in time).

Dynamic LCA provides results as indicators values in function of time, without a predefined time horizon. In order to compare conventional and dynamic LCA metrics, an appropriate time horizon was necessary to be chosen due to the definition of GWP100. As such, 100 years was considered as a point of comparison between the 2 approaches: i) percentage of contributors and their ranking were compared for a given scenario; ii) the ranking of scenarios and their relative disparity was analyzed. It should be noted that direct comparison by impact value is not possible as the 2 approaches have different metrics.

In this analysis, details of dynamic climate change impacts of 10 construction products family were individually analyzed. Results revealed the importance of considering temporal profiles of emissions over the long lifecycle of a building and their short and long-term effects.

In a short term analysis, inferior to the lifetime of the system investigated, CH_4 is for most construction product families a major factor of rapid temperature increase. However, due to a short-term persistence of CH_4 in atmosphere, CO_2 becomes the most important factor of global warming at long-term (e.g. at 100 years).

In case of bio-materials are included (e.g., P&IC family), accounting for the effect of biogenic CO2 makes the climate change scores remarkably different. In consequent, scenarios of forest management become important for the migration effort of GHG emissions.

An important conclusion is that the same quantity of GHG emission has a lesser impact when the emission is spread over a long time interval as if the emission is released instantaneously.

Finally, scenario analysis was conducted in order to identify the influence of changes on the product system (e.g., technological evolution). These results of the scenario analysis will be further discussed in the next chapter in order to provide some orientations for promoting sustainable developments in the building sector.

As a resume, dynamic LCA leads to important information about the amplitude and rate of change of climate change indicators versus time, which conventional LCA cannot provide. For a studied system: i) CRF indicator always increases due to the persistence of GHG in the atmosphere beyond the lifetime of the system; ii) GMTC is critical during the lifetime of the system prolonged with several years. Consequently, a relevant time horizon for impact observation could be the lifetime of the system plus several years beyond (up to ten). The dynamic indicators used have distinct meaning: when GHG emissions and captures take place, indicators can be positive (meaning damage) or negative (meaning a benefice). However, negative values of cumulated radiative forcing CRF indicator can co-exist with a positive mean temperature change GMTC, advising of the importance of the emissions dynamics when coupled with the dynamics of climatic effects (radiative forcing is a rapid response to GHG burden, while GMTC is a slow one).

It is important to note that when evaluating systems that are based on bio-based sources (e.g., electricity production by wood, bio-based insulation materials), dynamic LCA may inverse conclusions of conventional LCA results, and enhance the benefit of using certain bio-based materials as construction products.

The analysis of GHGs' contribution to climate change impacts through dynamic LCA is a very useful tool to help decision making because it allows identifying hotspots of climate change over time, scheduling optimal mitigation efforts.

Chapter 5

Orientations for DLCA users

5.1 Introduction

The previous Chapter 4 examined the feasibility of the proposed methodology of dynamic LCA applied to the building sector. Besides, the different climate change metrics are compared between each other aiming at identifying the relevance of using dynamic LCA in the building sector. Chapter 4 also showed the complexity of results interpretation due to the multiple unusual aspects such as the rate and amplitude of warming, emission timing, the influence of GHG mix. Following these first analyses of dynamic LCA results, this chapter seeks out at deepening our understanding of the dynamic results in order to identify their benefits and discuss how effectively DLCA can be used by different actors. This chapter pursues responses to our fundamental research questions raised in the introduction of this report (Section 1.3).

Putting our focus on searching for responses to these questions, we will propose several tools (e.g., table of identification of hotspots, ranking method) and orientations for DLCA users in the building sector. The orientation can be segmented into four destinations as in Figure 5-1: i) DLCA for building designers, ii) DLCA for manufacturers of construction products, iii) DLCA for public policy and environmental regulations, and iv) DLCA for R&D. The chapter tries to address each of the four aspects, but the discussion should be more deepened by further work.

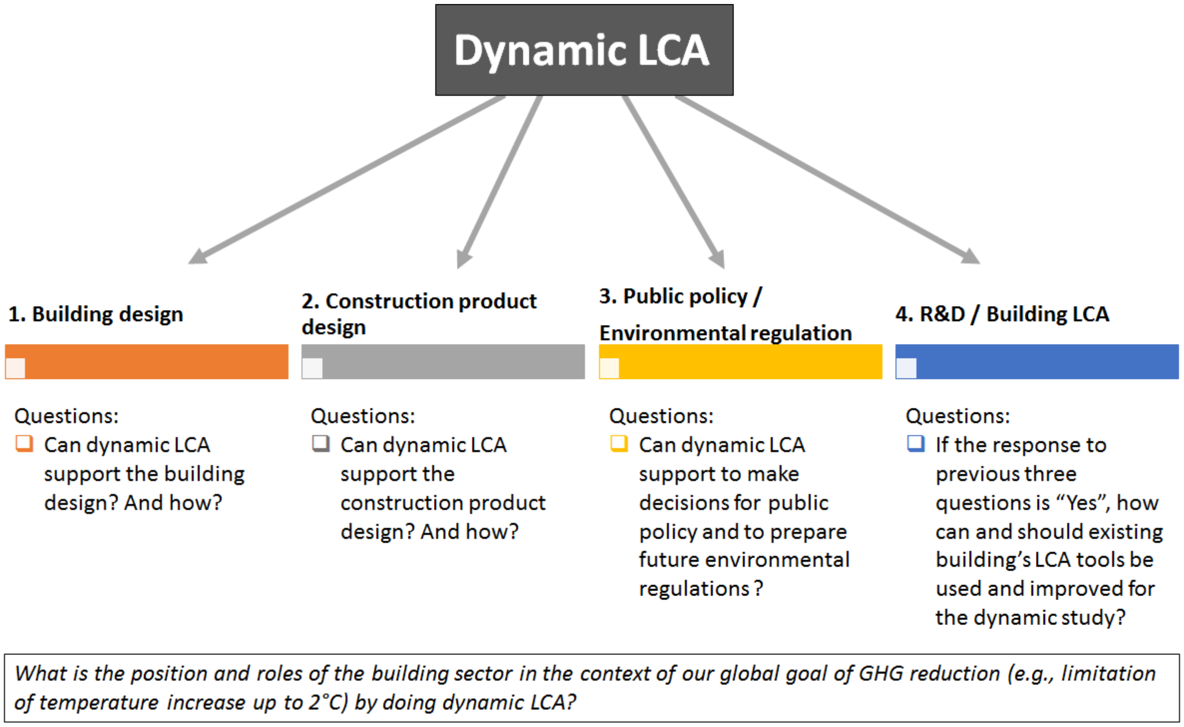


Figure 5-1: Orientations and questions for dynamic LCA utilizations in the building sector

Section 5.2 is at first dedicated to the brief discussion about the role of the building sector to meet our global GHG reduction targets with respect to the latest IPCC report. Then, we will discuss how the dynamic LCA changes and improves our understanding of environmental impacts, and how the interpretation could provide propositions for mitigation actions.

In Section 5.3, we will analyze the temporal profile of GHG emissions and captures through the life cycle of a building. This analysis allows for discussing how future environmental regulations should be improved (e.g., the objective of specific emissions reductions). At the same time, we will discuss how existing LCA tools in the building sector can be improved to shift from conventional to dynamic LCA.

5.2 Dynamic LCA for buildings and construction products design

5.2.1 Role of the building sector within the global warming target

The latest IPCC report (Oct. 2018) mentions that "*future climate-related risks depend on the* ***rate****,* ***peak****, and* ***duration*** *of warming*. (…) *risks are even more important if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C"*.

Nevertheless, the common practice of GWP of the horizon of 100 years is not consistent with setting temperature targets, and GWP does not account the specificity of GHG dynamic behaviors. The IPCC report also argued that "*Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and building), and industrial systems. There systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (….)"* (IPCC, 2018).

In general, GHG emissions through a building's lifecycle are generated at a long time scale (e.g., 50 or more years) because of the longevity of the buildings. Besides, together with emerging needs of management of existing buildings for the energy transition (Legrand and Fink, 2014; MEEM, 2016) and with new constructions due to the future development of cities (UN-Habitat, 2016), the building and construction sector may get an international dimension and a long term time scale. Meanwhile, the same IPCC report argues the importance of emissions reductions at earlier stages in the 21st century because global mean temperature increase is likely reaching 1.5°C in 2030 or at least in 2052 if anthropogenic-related warming will continue to increase at the current rate. Therefore, GHG mitigation efforts in the building sector are important to be implemented as early as possible for both renovations of existing buildings and new constructions. Otherwise, 1.5°C limitation pathways until 2100 require to decline CO_2 emissions by about 45% by 2030 compared to 2010 and to reach net zero emissions around 2050, according to the same report.

Moreover, the literature (e.g., Tanaka et al., 2010; Kirschbaum, 2014) acknowledges that the end point damages of climate perturbation are sensitive to at least 3 parameters: i) impacts related directly to elevated temperature (e.g., heat waves, coral bleaching, sea level rise, etc.); (ii) impacts related to the rate of warming (high rates of change give insufficient time for species adaptation leading to species extinction, etc.); iii) impacts related to cumulative warming (e.g., sea-level rise) because certain long-lived gases continue to cumulate their effects even several hundred to thousand years after emissions. The same emission is more dangerous when it occurs late in time than early because it adds a supplementary temperature increase at an already higher temperature.

In this context, the sustainability within the building sector involves not only the innovation of technical efficiencies but necessarily also material choices, material circularity, end-of-life and renovation strategies, and reduction of both embodied and non-embodied energy consumptions.

In case of *unavoidable* GHG emissions, the prospective scenarios related to technological innovation which allow both for lowering the temperature peak amplitude and for advancing the timing of temperature peaks would be the best solution facing risks related to warming. From now on, we need to evaluate risks related to warming combining different dynamic indicators. For example, we found that the same quantity of GHG emission has a lesser temperature increase when the emission is spread over a longer time interval. This is true for certain gases. However, when long-lived gases are distributed over a long time interval, it implies that cumulative effects also continue for a very long time interval as well (see a simple example in Figure 2-3). Conversely, short-lived gasses emitted in a short time interval create a significant temperature increase even though the effect does not last for a long time interval.

5.2.2 Identification of mitigation actions for impact contributors

In Figure 5-2, we see the temporal pathways of cumulative radiative forcing (CRF, first graph) and global mean temperature change (GMTC, second graph) for 10 construction product families with a time span encompassing the 3critical climate period with a temperature increase expected to exceed 1.5°C.

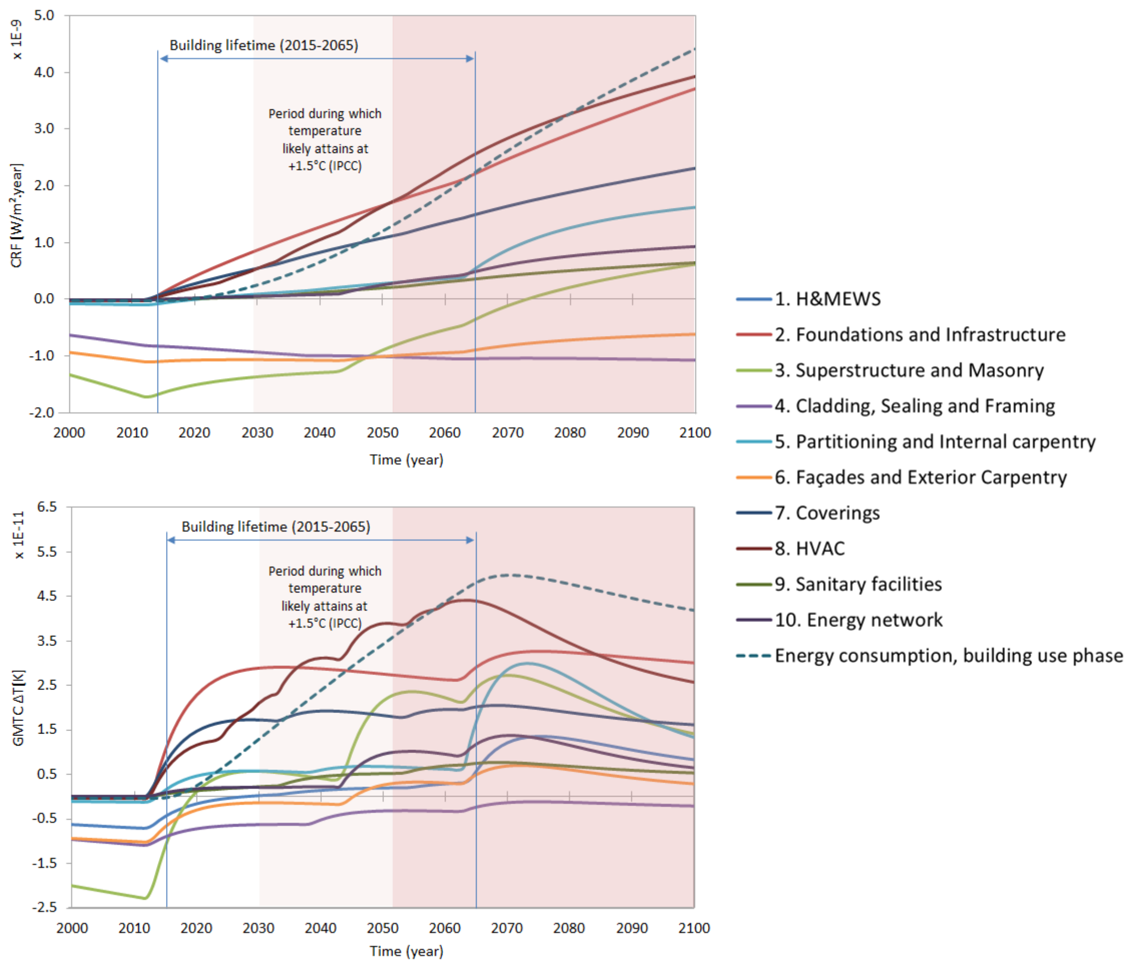


Figure 5-2: Global pathways of cumulative effect (CRF in the first graph) and temperature increase (GMTC in the second graph) of the testbed's building and impact positions regarding the intermediate global warming targets

In order to gradually stabilize global warming until 2100 without exceeding 1.5°C before 2100, it is needed to gradually stabilize CRF and to avoid the pics of temperature increase. On the basis of this specific case study, we have already observed in Section 4.5.2 that the important contributors to the impacts are the manufacturers of F&I (Foundations & Infrastructures) (group 2, red), Coverings (group 7, dark blue), and HVAC (group 8, dark red) family of the studied building. These three families have a high cumulative effect as soon as products were manufactured, which dominates during the lifecycle and beyond. However, their contribution of the end of life stage (the year 2065 and after) does not seem to be significant. That means concerned industries for these families need to make efforts for mitigating GHG emissions at the very first emissions related to the building construction and the fabrication of the construction products, in other words, today. There is no more acceptable delay for implementing actions for emission reduction.

In contrast, the other families do not have a relevant impact at the stage of products fabrication, while GMTC graph confirms the importance to reduce GHG emissions from the building waste management, at the end of life of each product, in order to avoid late and dangerous GMTC increase near the climate time-target. In the context of the national agreement for the green growth in France (MTES, 2016), it has been engaged to increase the rate of collection and recycling of certain materials (e.g., inert waste, glass wool) (see Annex IV that gives some detailed data). These agreements help the whole building sector to estimate possible pathways of GHG reductions in the future (e.g., by changing building typology or by promoting material circularity) as exemplified in Section 4.5.3.

Concerning the impacts related to energy consumption during the building use (blue dashed line), even if this building is designed with a high thermal performance (described in Section 4.2), the constant GHG emissions due to the daily household activities during 50 years make the impact longer-lived. The reduction of energy consumption and the integration of more renewable sources into the power grid are necessary as early as possible.

On the same graphs (Figure 5-2), we can also observe that the occurrence time of temperature peak is not always at the same moment, depending on the waste treatment technology and the mix of GHG emissions. Regarding the S&M family (group 3, clear green), it creates punctual warming with the peak temperature at around 2055 and 2070. Nevertheless, the effect of CO_2 uptake by trees growth is lasting in a significant period, and thus the cumulative effect (CRF) remains low level or even negative. For this family group, concerned industrial sectors can concentrate their actions on eliminating the punctual emissions by managing the waste treatment.

The new dynamic metrics emphasize the importance of differentiating mitigation actions by types of gases. Because of the variability of the lifetime of gases, the duration of the ecosystem's risks related to climate perturbation (e.g., warming in our case) is also variable in function of the gas. As we saw through our case study in Chapter 4, short-lived gases (e.g., CH_4, HFC-134a) have an impact in a short time scale provoking a temperature peak, while long-lived gases (e.g., CO_2, N_2O) have persistent impacts for long periods. Also, the temporal profile of emissions (pulse or continuous, duration of emission) determines if the effect spreads on a long time scale or not. Based on our case study, we could resume our critical findings in the following Table 5-1. This table aims at a categorization of different actions for GHG reduction by targeting various aspects of dynamic climate impacts. This kind of synthesis can provide the first guidance for actors in the building sector so that they can establish their building scenario. It helps at acquiring a global vision on which materials/products have which types of climate-related risks and what are the appropriate options to reduce emissions more precisely than conventional LCA can provide.

The table was created for the identification of mitigation actions based on our wood-based building. Developing such kind of table (the content of which will be different depending on building typology) would be helpful for other typologies of buildings (e.g., concrete, block).

Table 5-1: Identified GHG mitigation actions for different building's actors (based on our testbed case of the wooden building)

Construction product or contributors that have…	Contributors, life cycle phase	What are the consequences?	Actions for reducing climate-related risks
1. Important emissions of CO_2, N_2O, and other long-lived GHG gases (lifetime more than 100 years)	Construction product families at the product fabrication phase (A, B) • H&MEWS • Foundations and Infrastructure • Partitioning, Lining, Suspended Ceiling, Interior Carpentry • Façades and Exterior Carpentry • Coverings • Sanitary Facilities	• Cumulated effect (CRF) persistent for a long time, inducing damages even decades or centuries after the last emission.	• Drastically *reduce especially CO_2 emissions (the longest lifetime*) • If important long-lived emissions occur late in time, it is even more important to reduce that late emissions than earlier ones.
2. Important emissions of CH_4, HFCs, and short-lived GHG gases (up to 100 years)	Construction product families at the product fabrication phase (A, B) • HVAC (due to HFC-134a use)	• Rapid increase in temperature	• Eliminate this kind of emissions (e.g., replace HFC-134a by other gases with a *lower specific radiative forcing*)
3. End-of-life with landfill	Construction product families at the end of life phase (C) • H&MEWS • Superstructure and Masonry	• Generation of biogenic CH_4 late in time, with rapid increase in temperature	• Avoid landfilling, promote other processing routes *without any GHG emissions. Attention must be paid at all GHG (avoid*

	• Partitioning, Lining, Suspended Ceiling, Interior Carpentry • Façade and Exterior Carpentry • Coverings • Sanitary Facilities • Energy Networks		*temperature peaks near and after climate target)*
4. Important amount of bio-based material/product	Construction product families: • H&MEWS • Superstructure and Masonry • Roofing, Tightness, Framework, Flashing • Façade and Exterior Carpentry	• Uptake of atmospheric CO_2 occurs during decades to centennial periods before material/product fabrication • Beneficial impact by reducing atmospheric radiative forcing and temperature	• Effective forestry management can be established to allow for neutralizing the effect of GHG emissions by a sufficient CO2 uptake with appropriate timing of capture.
5. Regular activities (e.g., maintenance, replacement, energy consumption)	Construction product families: • Coverings • HVAC • Sanitary Facilities End-user's energy consumption	• Associated GHG emissions occur regularly • Emissions distributed over a long time cause lower rates of temperature increase but same cumulated CRF at long term	• Replace short lifetime products by ones having a long lifetime while preventing the end-of-life too emitting. • *Avoid fabrication emissions near climate target time* based on the concept of circular economy • Drastically reduce energy consumption or CO_2 emissions all along the building lifetime.

5.2.3 New metrics and analysis at the building scale

In the following, a new angle of analysis is proposed based on the dynamic LCA results, by combining the temperature peak attained and its timing for each construction product family. Instead of a single score analysis (e.g., GWP) as in conventional LCA, we conduct a two-dimensional impact analysis of each family, plotted in Figure 5-3. The raw data of the graph are presented in Annex IV. The axis x represents the relative time where temperature attains the peak of a given family with respect to the time of the temperature peak of the overall building. The axis y represents the ratio between the temperature peak due to a given family and that of the overall building. The coordinates of a point are given by:

$$(relative\ time, GMTC\ contribution)_i = \left(\frac{time_{max,i} - time_{max,building}}{time_{max,building}}, \frac{\Delta T_{max,i}}{\Delta T_{max,building}} \right) \quad Equation\ 5\text{-}1$$

According to Figure 4-14, the temperature increase of the entire building attains its peak of 2.6E-10 K at the 55th year (in 2061). The temperature peak due to the HVAC family represents around 25% of the building's peak at the 48th year (in 2048). The relative time is calculated by referring to the 55th years (which is the peak's time of the building), i.e., -0.14.

The results presented in Figure 5-3 implicitly depend on the GHG nature since the temperature response to atmospheric perturbation, i.e., atmospheric concentration variation of gases and variation of radiative forcing, depends on the mix of GHG emissions. Globally, the temperature peak of each substance comes several years after the latest emission, which is related to product fabrication or waste treatment.

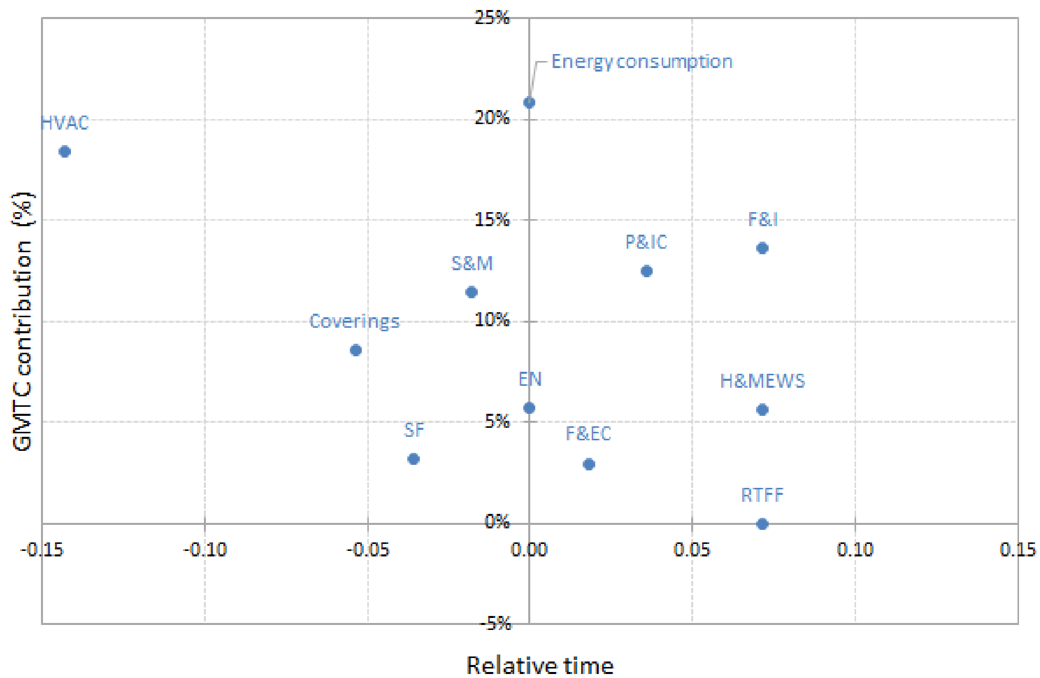


Figure 5-3: GMTC contribution of the construction product families and operational energy consumption with respect to the whole building

This figure shows a two-dimensional comparison of the building contributors (impact level and impact time) and enables identification of action priorities in a new way as compared to GWP-based single score rankings.

The first way of ranking is defined as "Impact-first (and time-second)" ranking. The priority is defined by order of impact level, from a high to the low level, and if several elements have similar levels, the relative time is used as a second criterion for classing.

The second way of ranking is "Time-first (and impact-second)" ranking. The priority is at first defined by order of relative time of the temperature peak, from the latest to earliest, and then by the impact level if the timing is similar for several contributors. We consider that the late emissions should be treated as a high priority for GHG mitigations because of the characteristic of global warming that late emissions are more dangerous than early emissions due to the cumulative effect of environmental perturbations (Kirschbaum, 2014).

Table 5-2 shows the action priority based on these two raking metrics, compared to conventional LCA ranking.

In order to facilitate the comparison, for the conventional LCA results, colors were added for highlighting the ranking: the three most influential families are colored by a red gradient from the most prominent family in dark red; the three less influential families are colored by a green gradient (the less impacting in dark green). So a color makes a given contributor recognizable for its position in the three rankings.

Table 5-2: Action priority for climate impact reduction from the case study

	Conventional LCA ranking	**"Impact-first" ranking**	**"Time-first" ranking**
1	HVAC	HVAC	F&I
2	S&M	F&I	H&MEWS
3	F&I	P&IC	RTFF
4	H&MEWS	S&M	P&IC
5	Coverings	Coverings	F&EC
6	RTFF	H&MEWS	EN
7	P&IC	EN	S&M
8	F&EC	SF	SF
9	EN	F&EC	Coverings
10	SF	RTFF	HVAC

We remind that the presented rankings were established by our specific case study, which is not representative of the whole building sector. However, we could still observe the similarity of conventional LCA ranking between our case study and the available statistics of the Observatory project, which is a preparation project of the new energy and environmental regulation (MTES, 2019). The supplementary information in Annex IV presents the comparison with Observatory project that validates our conventional LCA rankings in Table 5-2.

With the “Impact-first” ranking, the action priority ranking differs from those based on conventional LCA. The most important differences are observed for “time-first” ranking method. In this latter metric, HVAC family group (which is the most influential) even falls into a less important level because this family gives the earliest temperature peak compared to any other family groups (see Figure 5-3). However, the disadvantage of this ranking metric is that it can consider certain families as a high priority action, while their contribution to warming is small (e.g., RTFF group in our case study). Conversely, certain families having a high contribution to temperature increase such as HVAC family has a lower priority because of their early temperature peak. To overcome this problem, giving a threshold of GMTC contribution level (e.g., families having the GMTC contribution higher than 10% is prioritized) could be a solution.

Figure 5-4 demonstrates how the contribution of the testbed building to GMTC indicator is placed within our goal of temperature limitations at 1.5°C by 2050. The 10 families of construction products and operational energy are considered; the sum of these two groups is considered as “building (total).” The relative GMTC and time for each element are thus calculated with respect to our global objective of 1.5°C by 2050 (target values):

$$(relative\ time, GMTC\ contribution)_i = \left(\frac{year_{max,i} - year_{target}}{year_{target}}, \frac{\Delta T_{max,i}}{\Delta T_{target}} \right) \qquad Equation\ 5\text{-}2$$

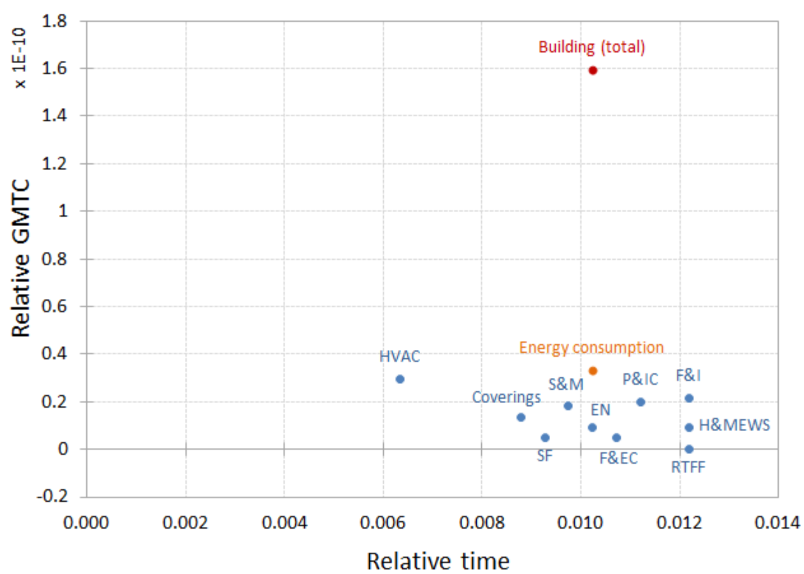


Figure 5-4: GMTC contribution of the whole building, construction product families, and operational energy consumption with respect to the global target of temperature increase limitation of 1.5°C in 2050

We observe that the contribution of only one building (the case study) to the 1.5°C increase is extremely small, by order of 1E-10. In order to clarify the role of the building sector within the objectives of GHG mitigation and to help effectively political decisions, it will be important to perform the contribution analysis at the scale of the French national strategy of renovation and new constructions. The same Figure 5-4 leads to an important argument as the following.

The major conclusion from this analysis is that the temperature peak of all components are found in a very critical area where we must prevent temperature increase.

5.2.4 Prospective scenario analysis by dynamic LCA

In Section 4.5.3, prospective scenarios of the building were proposed and analyzed. The results obtained with different metrics of climate change were compared. Some key features found through this comparative study are the followings:

1. Concerning the end-user's energy consumption, emissions can be significantly increased depending on the equipment's technical degradations and their accumulation in time. In this case where emission profiles are dynamically changing over a long time interval, dynamic LCA accounts more precisely the influence of system degradations than conventional LCA.
2. For the scenarios of technological change, dynamic LCA is necessary: i) when evaluating bio-based products in order to account for the benefice of CO_2 uptake, ii) for avoiding late emissions when replacement/renovation takes place.
3. The end-of-life technologies scenarios are important to be evaluated with dynamic LCA. The emissions related to the end-of-life occur late in the calendar, at around 50th year in our case study. The influence of this important time delay of emissions (more than several decades) on LCA results cannot be accounted for by conventional LCA.
4. When considering the landfill scenario as the end-of-life process, dynamic LCA accounts for the effect of the delay of biogenic CH_4 release that causes a sudden increase in temperature. In this case, dynamic LCA provides useful information about the level and timing of the impact, notably with respect to the climate target.

5. The prospective scenario concerning the energy efficiency of product manufacturing (background processes) does not show significant differences regarding the baseline scenario when using different metrics.
6. For certain industrial sectors especially involving biomass resources like wood, dynamic LCA analysis is beneficial because of the presence of CO_2 uptake and the release of biogenic CO_2 and CH_4. We observed the benefit of using bio-based materials (e.g., insulation materials in our case study) that was revealed by dynamic LCA.
7. Concerning the evaluation of future electricity production mix, the results are inversed between conventional and dynamic LCA due to the methodological difference regarding biogenic CO_2. Future mixes have an increasing rate of bio-based electricity generation. Because electricity is permanently used during the building use phase (50 years in our case), the temporal discrepancy between CO_2 uptake and its releases into the atmosphere has a significant influence on LCA results. Dynamic LCA revealed the disadvantage of integrating bio-based electricity production when compared to the climate-related performance of nuclear power generation.

Globally, the analysis of prospective scenarios has revealed the usefulness of dynamic LCA: i) when accounting for biogenic CO_2 and CH_4, ii) when emissions are spread over time (e.g., end-user's energy consumption level change) or iii) emissions occur later in the calendar (e.g., end-of-life technology change). For scenarios mostly related to operational energy consumption (e.g., equipment efficiency loss, change in occupant number), the conclusion between conventional and dynamic LCA was the same. Moreover, the new metrics (impact and time combined analysis) introduced in Section 5.2.3, allows evaluating the advantages or disadvantages of that prospective scenarios compared to the baseline scenario, not only by an impact level but also by the timing of the temperature peak.

In the following, the comparison is presented between the baseline scenario and prospective scenarios. Therefore, relative GMTC peak and relative time at which temperature attains its peak were calculated with respect to the baseline scenario peak. The results are plotted in Figure 5-5 with the red circle for the worst case scenarios and the blue diamond for the best case scenarios (presented in Table 4-7 in Section 4.4.5). The raw data of the graph is found in Annex IV.

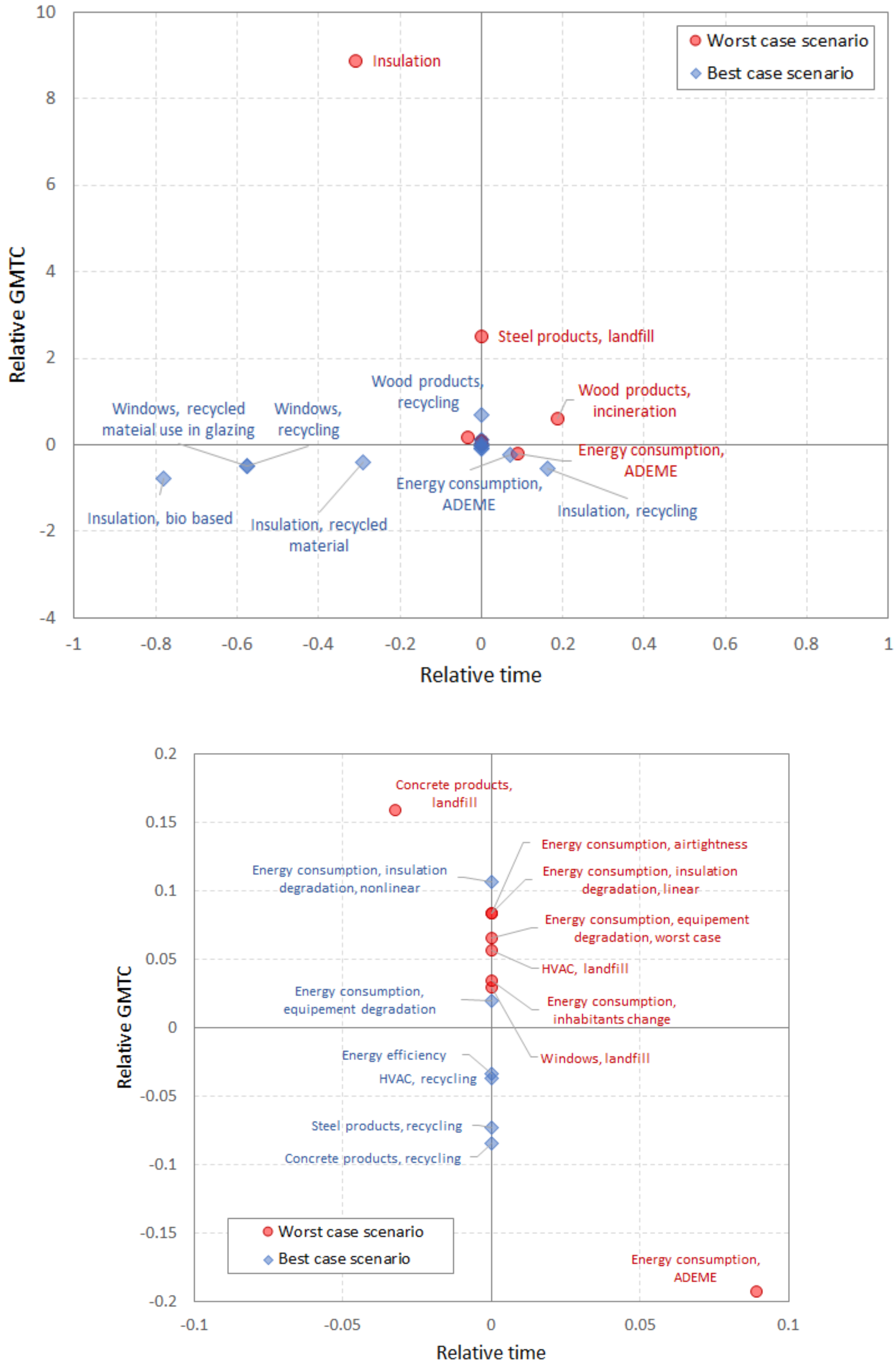


Figure 5-5: Relative GMTC impact and relative time of prospective scenarios with respect to the baseline scenario (points represent the worst (res circle) and best case (blue diamond)). The second graph is a zoomed one from the former graph.

The scenarios that are placed in the lower-left area, with negative values for both relative GMTC and relative time, are beneficial because they can reduce the temperature peak and move it to an earlier time. In contrast, the scenarios represented in the upper-right area should be avoided because they provoke a higher temperature peak and it arrives later. In our case, the incineration of all wooded wastes causes a 60% higher and 20% later (corresponding to 11 years later) temperature peak as the baseline scenario. However, it is not simple to qualify the performance of certain scenarios found either in the upper-left or in the lower-right quarters. The analysis of the effects of the temperature peak and its timing should be deepened.

For example, we can observe in the same Figure 5-4 that the use of the innovative insulation materials (*"Insulation, bio-based," "Insulation, recycled material"*) allows a better solution. While, when we consider the recycling scenario of conventional insulation material (*"Insulation, recycling"*), the end of life process will produce a smaller peak than the baseline, but this peak is placed later in time. This solution could be acceptable if emissions are compensated by other rapid capture processes, for example, biomass growth. In the context of GHG neutrality close to and after the climate target, a solution for compensating GHG emissions could be the system expansion by adding to the building system a bio-based system, who's management should be correlated in order to achieve objectives of zero temperature increase and zero cumulative radiative forcings. Finally, the "worst scenario" presents the highest peak. Even if it is placed earlier in time, a higher temperature contribution is hardly acceptable. In this case, the GHG composition is important because persistent gases are more hazardous due to cumulative effects.

5.3 Dynamic LCA for building actors and regulation

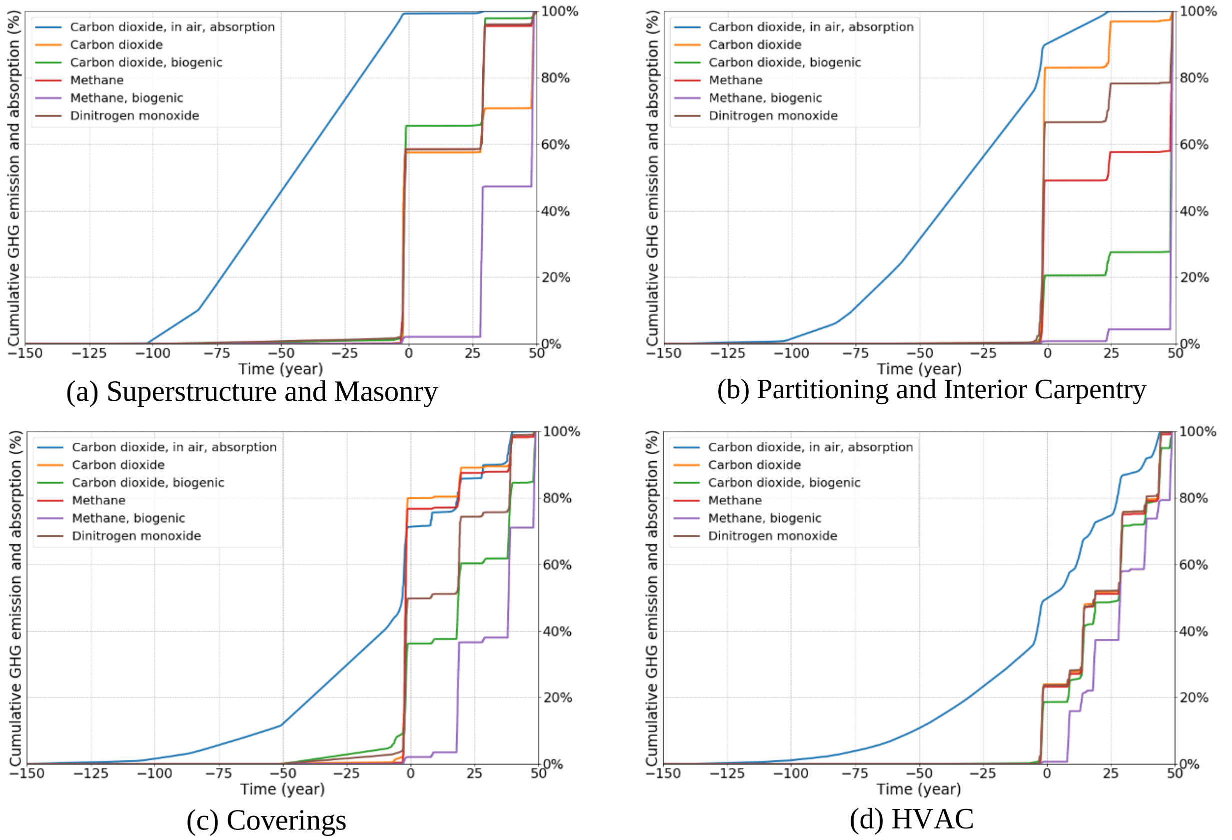
5.3.1 Emission profile analysis

We remind that one of our fundamental research questions is "does dynamic LCA change decision makings?" By performing dynamic LCA study through our testbed case and the results' synthesis in Chapter 4, we figure out the importance to know "which gases are emitted at what time?" Knowing the response to this question helps to define the typology of warming pathways, i.e., rate, peak, and duration of temperature increase, and system risks related to warming. Furthermore, it helps to define the actions for GHG mitigation and set targets for future environmental regulations for different industrial sectors.

In the building sector, a temporal emission profile may depend on the building's typology, lifetime, used construction materials and products, activities during the building use phase (e.g., maintenance, replacement, energy consumption), and prospective scenarios (technology evolution) of the studied system. Therefore, the temporal emission profile can be very case-specific. However, an LCI calculation at daily time step (in our case) or even smaller one leads to very heavy calculation time and may not be realistic when evaluating long-lived systems as buildings. Therefore, a simplified approach for defining typical temporal emissions profile greatly helps the actors of the building sector for making dynamic impact assessments. The conventional LCA uses a simplified LCI with no temporal differentiation. Also, in the French building sector, EPDs represent the impacts aggregated at the foreground process level without knowing if background processes emissions are distributed over a short (i.e., thus temporal differentiation can be simplified or even ignored) or long period (i.e., thus emissions should be temporally differentiated).

In this context, we intend to propose a simplified temporal LCI on the basis of our case study.

In Figure 5-6, we illustrate the cumulative percentage of emissions and absorption of the principal GHG (CO_2, CH_4, and N_2O) through the lifecycle of the building. Four examples are presented: (a) S&M family group, (b) P&IC family group, (c) Coverings family group, and (d) HVAC family group. The beginning of the building use (Phase B of the building lifecycle) is placed at time 0, and the end of life is placed at time 50. Thus, emissions placed before time 0 are generated by products fabrication for the building construction and those positioned between time 0 and 50 are related to the maintenance, replacement, and end-of-life processes. These emissions correspond to the contributor "construction product." Emissions related to the three other contributors, i.e., "energy consumption," "water consumption," and "on-site construction consumptions" are not yet investigated. The start time of the analysis is fixed 150 years back from time 0 that corresponds to the beginning of the building's use phase. For instance, in our case study based on the default production time defined in DyPLCA temporal database, the wood employed as a raw material has a growth time of 140 years.



(a) Superstructure and Masonry

(b) Partitioning and Interior Carpentry

(c) Coverings

(d) HVAC

Figure 5-6: Cumulative percentage of GHG emissions and capture of four construction product family through the lifecycle of the building (a: S&M, b: P&IC, c: Coverings, d: HVAC)

The global observation is that the emission profile very sharply follows each foreground activity (e.g., construction, replacements, end of life). This fact means that most product manufacturing occurs within a short time scale, roughly less than one year. The absorption of carbon dioxide (blue) has a different profile which will be discussed in the following paragraph. From the figure, the emissions taking place in the past are even not visible, and most emissions occur within several years back from the foreground activities. This fact implies that dynamic LCI modeling can be performed at the annual level or even at the foreground activity level for the "construction product" contributor, i.e., at the level of building's life cycle phase as defined in the EN 15978 standard (CEN, 2012a). This finding confirms the usefulness of the simplification adopted in French EPDs to model static LCI. As a result, dynamic LCA can be performed by using EPDs enriched with supplementary information on principal GHG emissions and by calculating LCI with an annual step or lifecycle phase-based step, as shown in Figure 5-7.

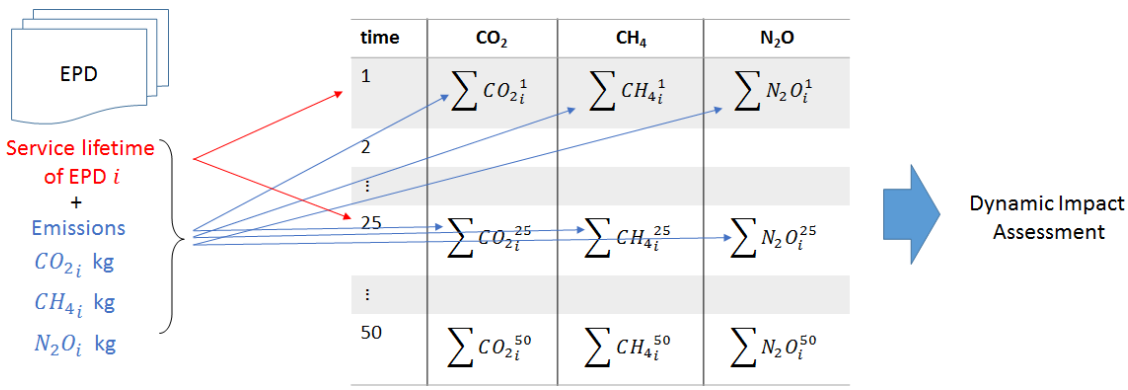


Figure 5-7: Dynamic LCI calculation using the building's EPD

In Figure 5-6, we also find the different typology of emission profiles in function of the product family and the nature of GHG. In the same figure, comparing between (a) and (b), the emission of CO_2 (orange) from the construction phase (around time 0) ranges between 60 and 80%, while biogenic CO_2 (green) ranges between 20 and 65%. Looking at year 25 always in (a) and (b), CH_4 (red) emission from the replacement varies from 60 to 95%. Now, looking at the graphs (c) and (d), the emissions are more distributed because of short service lifetime of the products. Besides, we observe that an important amount of biogenic CH_4 emissions is allocated to the intermediate and end-of-life phases, but not to the construction phase, for all four groups. For the P&IC family group (b), almost 95% of biogenic CH_4 is emitted at the end of life stage. This fact confirms the sudden increase in temperature due to biogenic CH_4 emissions from the landfill scenario (see Figure 4-26).

Now, in order to investigate the sensitivity of LCA results to LCI's time step interval and to validate our proposition of a simplified LCI, we compare the CRF and GMTC indicators for the construction products based on two types of LCI: 1) dynamic LCI generated by DyPLCA at daily time step and 2) simplified LCI at yearly time step. The simplified LCI was obtained from DyPLCA LCI by aggregating emissions at a yearly time step. The three other contributors are not analyzed here, and only emissions of CO_2, CH_4, N_2O, and HFC-134a are considered in this analysis. The results are presented in Figure 5-8.

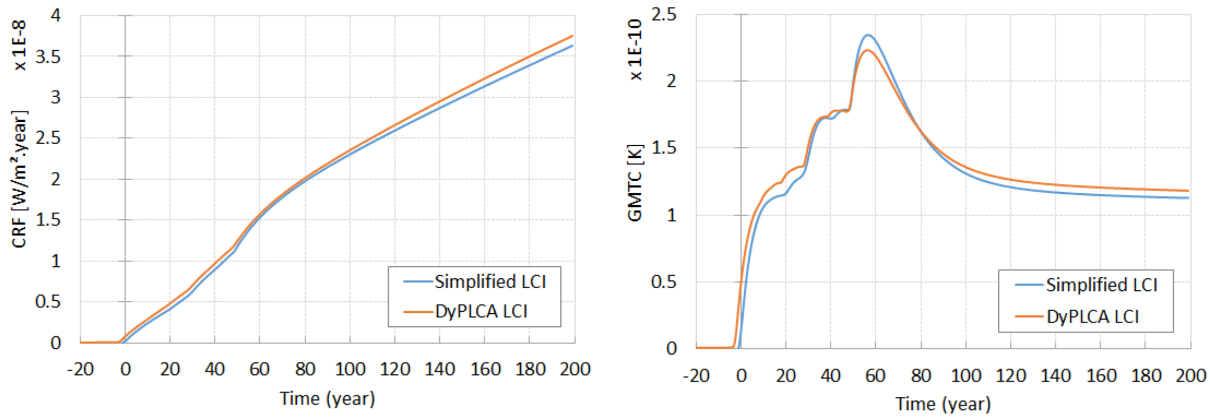


Figure 5-8: CRF (left graph) and GMTC (right graph) indicators calculated with DyPLCA LCI (daily time step, orange line) and simplified LCI (yearly times step, blue line) for the contributor of construction products

At 100th year, the CRF result with the DyPLCA LCI is only 2% higher than that with the simplified LCI. For GMTC indicator, the result with the simplified LCI is 5% higher than that with the DyPLCA LCI at the highest temperature peak.

By aggregating emissions at a yearly time step, the emissions at the end of life stage become significant enough that they provoke a higher GMTC than the those obtained by DyPLCA where the LCI is distributed over a longer period. The responsible gas of this temperature increase is biogenic CH_4.

Through this analysis, it is found that with a yearly step the difference between the two simulations remains marginal so a yearly time step for LCI may be satisfactory. However, it also reveals that temperature change is sensitive to the time step of CH_4 emissions. The estimation of temperature peak would require time steps smaller than one year in case of short-lived GHG.

However, the typology of emissions (emission timing, mix of GHG, etc.) is dependent on the typology of buildings (main materials, structure types, etc.). More case studies and analyses are necessary to confirm that the yearly time step can be used for dynamic LCI.

5.3.2 Carbon dioxide removal (CDR) by the building sector

The IPCC reports mention the importance of carbon dioxide removal as a strategy to meet the target that limits global warming to 1.5°C. According to the report, the use of carbon dioxide removal (CDR) on the order of 100 to 1000 Gt CO_2 over the 21^{st} century is accounted for in order to compensate for residual emissions (IPCC, 2018). In the building sector, sustainable forestry management (afforestation or reforestation) possesses potential of CDR for wooden-based buildings. The afforestation represents the case where the trees are artificially planted to be used in the construction sector, and the reforestation represents the case where the trees are replaced in natural forest (Fouquet et al., 2015).

One important aspect to note is that in DyPLCA temporal database, a constant absorption rate of CO_2 by trees is considered, during the tree growth period varying from one species to another (e.g., the growth period of the oak tree is considered 140 years, while 80 years for pine and five years for eucalyptus). However, in reality, the duration of CO_2 uptake may vary from one forest to another due to different conditions such as biological, chemical or climatic conditions. The rate of absorption may also vary in function of the tree age. These variable rates are not considered in the simulations.

To understand the effect of the absorption of CO_2, three types of absorption profile over 100 years are considered. In Figure 5-9, the cumulative percentages of CO_2 absorption are illustrated. The A scenario considers the cumulative absorption following the logarithmic line. The B scenario represents the linear absorption. Finally, the C scenario considers the cumulative absorption following the exponential line. For the three cases, the total mass of absorption is 100 kg reaching 100% of absorption in 100 years. Figure 5-10 illustrates the calculation results of CRF at the left and GMTC at the right for the absorption cases A, B, and C for 200 years.

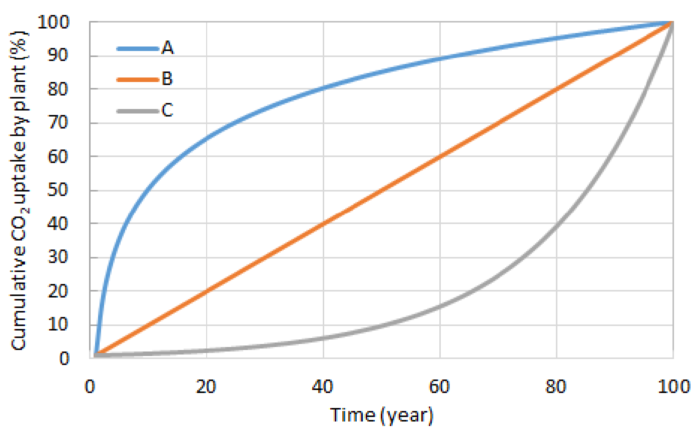


Figure 5-9: Three cumulative absorption profile for carbon dioxide

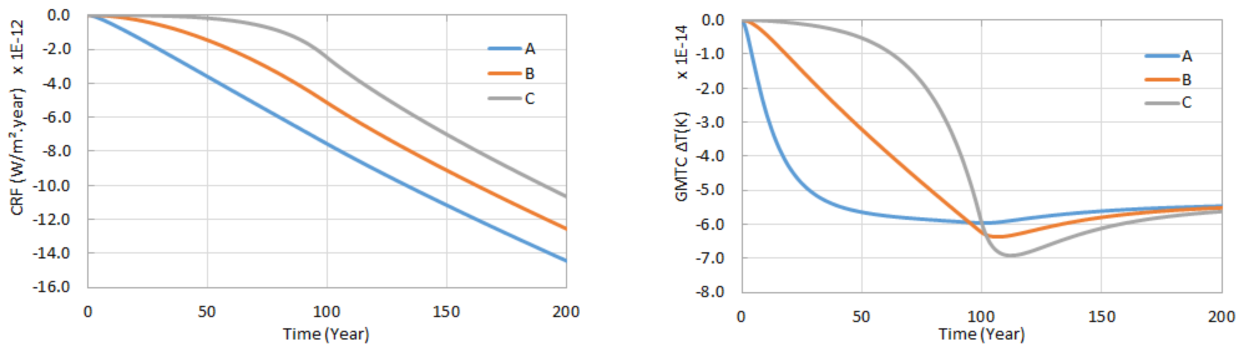


Figure 5-10: Dynamic CRF (left) and GMTC (right) calculated over 200 years for carbon dioxide absorption for three cumulative absorption profiles (A: logarithmic, B: linear, C: exponential)

For CRF indicator, case A almost linearly decreases and reaches -7.58E-12 W/m².year at 100 years, that is 47% lower than CRF of the case B at 100 years.

Meanwhile, the case C gradually decreases until around 100 years and reaches at -2.53E-12 W/m².year at 100 years that is 51% higher than CRF of case B at 100 years. The three results would arrive at the convergence in a very long time, determined by the remaining CO_2. This analysis confirms that accounting for CO_2 absorption in the early stages of the building's lifecycle could be more beneficial than late accounting of CO_2 in terms of cumulative effects of warming.

For GMTC indicator, case A steeply decreases until 25 years, and temperature stabilizes early comparing to two other cases. Its temperature peak is -5.96E-14 K at 100 years, that is 6% higher and 6 years earlier than the case B. Meanwhile, the case C slowly decreases exponentially and reaches -6.93E-14 K at 111 years, that is 9% lower and 11 years later than the case B. The temperature decrease rate within 100 years varies significantly, while looking at the horizon of 200 years the three scenarios reach the same level.

With climate targets situated in the middle of our century, short term variations become of great importance and need to be accounted for in the system simulation.

Temperature decrease rate greatly differs from a case to another, within the horizon of 100 years. However, the three types of temperature decrease were stabilized at a certain level much earlier than CRF. When choosing wooden-based construction products, using an amount of wood in an earlier period makes a significant gain in terms of climate indicators than using the same amount of wood spread over a long time interval.

In other words, CO_2 capture in early periods is more beneficial for the system performance than the same capture occurring near the climate target time.

These analyses related to CO_2 absorption reveals the importance of dynamic LCA because the absorption timing significantly affects its benefice on GMTC and CRF, especially in a short time (within a century). Therefore, studying the CO_2 absorption/emission profiles and their effects could help to establish effective afforestation/reforestation strategies for sustainability in the building sector.

5.4 Conclusion

In this chapter, our primary research questions (Section 1.3) are first reformulated with the objective to orient the use of dynamic LCA towards its effective application at three levels of study: building design, construction product design, and future environmental regulations. Through deepening the interpretation of dynamic LCA results obtained in Section 4.5, we proposed new tools for evaluating environmental performances of the testbed building and for helping decision making. The different characteristics of warming (peak and timing) other than that of GWP indicator (cumulative effect without emission timing) are integrated into our tools because the evaluation only by the classical GWP does not cover every risk related to warming. This more complex analysis becomes necessary in the present due to the more and more nearer climate target time.

A table was proposed to identify different mitigation actions in function of the typology of emissions (type of gases and temporal profile of emissions) on the basis of the case study. The table gives to the actors of the building sector a global vision for designing buildings with more detailed understanding regarding environmental risks than those provided by conventional LCA. The development of the table with a variety of building typologies (e.g., structure type, principal materials, building usage type) will help to enlarge options of decisions.

A classification method was proposed for analyzing the contributors and the prospective scenarios, based on the two-dimensional assessment instead of a single score-based comparison as in conventional LCA. It attempts to evaluate both the peak temperature and its timing of each element under study. This enhanced method of analysis and classification has a strong potential for ranking action priorities, more precisely as the conventional LCA.

Finally, a simplified way to build a temporal LCI based on EPDs information was proposed by using simplified temporal profiles of gases, for both emission and absorption, for the principal GHG (CO_2, CH_4, and N_2O). This analysis showed the possibility of the simplification of dynamic LCI at least by aggregating emissions at yearly time step or even by aggregating at each life cycle sub-phase (e.g., construction, repair, maintenance, replacement, end of life).

By investigating the effect of different absorption dynamics of CO_2, it was possible to show that CO_2 capture in early times is more beneficial for the system performance than the same capture occurring near the climate target time. Also, short term variations of the capture dynamics are to be accounted for in the system simulation, given the urgency of the climate issue. These conclusions can be used for extending the building system boundaries by including biomass systems for a compensatory action (e.g., forestry), searching for the optimal timing.

Chapter 6

Conclusions and perspectives

6.1 Conclusions

Most of LCA studies applied to the building sector have been based on a *status-quo* approach, while building systems have a lifetime long enough to take system degradations and advantages of emerging technologies into consideration for environmental calculation modellings. At the same time, building end-users, as part of a building system, have changed and continue to change their behaviors at different time scales, and thus change energy and water consumption over the building use phase.

The present thesis proposes a dynamic LCA methodology applied to the building sector that incorporates three distinct dynamic aspects into LCA:

1. Dynamic behavior of buildings over the long lifecycle into LCI modelling
2. Temporal distribution of LCI following the production and supply chain within the life cycle system
3. Dynamic impacts calculations combining dynamic LCI with time specific LCIA method

Together with the above temporal considerations of building systems, the full dynamic LCA methodology was developed based on the overall LCI model developed in the DyPLCA project. The DyPLCA model allows for simulating emissions and impacts pathways as a function of time. Climate change impacts (radiative forcing and global mean temperature change) were evaluated in our work.

The developed methodology was finally applied to a case study with three attached single houses. Through the case study, we analyzed the influence of dynamic LCI on the LCA results, comparison between conventional and dynamic simulations, and identification of most important contributors. The case study demonstrates the effectiveness of dynamic LCA, in case of climate change impact, regarding three distinct orientations: building design, eco-design of construction products, and public policy. The following paragraphs resume our findings.

Development of the methodology of dynamic LCA for buildings

For the assessment of the dynamic impacts, the developed methodology makes the most effective use of:

- Existing inventory datasets (ecoinvent or INIES that is more specific to the building sector) and dynamic energy simulation tool (COMETH)
- Building's dynamics database, to characterize building systems by temporal information
- Matrix-based LCI model using a standard LCA software (e.g., SimaPro)
- DyPLCA temporal database, to build the process network from LCI matrixes
- DyPLCA web application to solve dynamic LCI model and to trace emissions over the process network
- and dynamic LCIA calculation tool (climate change impact) for dynamic impact assessments

At the level of the building system dynamics (concerning 2nd point), this thesis work contributes to dynamic LCA by constituting a database of time-varying parameters at different levels of building systems. These parameters allow characterizing building-related technologies, end-users, and other external factors by temporal information. Collected time-varying parameters are then integrated into the LCI model and, after impact calculation, they allow a deeper analysis of the building performances in time. Thus, the enrichment of the database is an important step leading to proper understandings of dynamic impacts.

In order to calculate temporal emissions (concerning 5th point) in the case of buildings, some adaptations of the DyPLCA capabilities were necessary to take into consideration the different phases of a building lifecycle, which is unusually long. The important adaptation deals with the definition of the temporality of processes, supply, and activities that interfere after the initial construction, in other words, during the building use phase. More precisely, these processes represent maintenance, replacement, renovation, demolition and the process of household's water and operational energy consumption. This adaptation was progressively met through the case study.

The case study showed the feasibility of dynamic LCA of buildings by multiple simulations based on which we could have feedbacks to consolidate dynamic LCI modeling and the global methodology of dynamic LCA of buildings. This case study is the very first attempt of a complete dynamic LCA study of buildings, and, at the same time, demonstrates the usefulness of dynamic impact assessments.

Conventional LCA vs. Dynamic LCA

Results comparison between conventional (GWP100) and dynamic metrics (cumulative radiative forcing, global mean temperature change) shown that dynamic metrics are useful for identifying mitigation actions relevant for a various typology of GHG emissions and different types of climate-related impacts.

It was substantiated by our specific case study (three single attached houses based on wood) that the same quantity of GHG emissions has a lesser impact when the emissions are spread over a long time interval than when emissions occur instantaneously. It is of crucial importance to take into account the lifetime of different GHGs, the profile and the moment of emissions, in order to make effective decisions.

For example, CH_4 is a short-lived substance (12 years of lifetime) and provokes a rapid increase in temperature without long period effect. Whereas radiative efficiency of CO_2 is inferior to those of CH_4 (GWP100 of CH_4 = 25 by IPCC 2013) and the temperature increases slower than in case of CH_4, climate perturbations are much more persistent due to the long life (quasi-infinite) of CO_2. The nature of GHG influences thus differently the GMTC indicator (level and timing), and the related endpoint damages (e.g., ecosystems adaptation to higher temperatures). Complementary, the cumulative indicator CRF accounts for all GHG and it 'memorizes' the emissions history such that even if gas is very short-lasting, its influence is not erasable at all, especially on endpoint damages like sea level increase.

The dynamic impact analysis was performed for each of considered ten construction product families. It was observed that each family have its climate footprint (dynamic indicators in function of time) due to the different typology of emissions (mix of GHG, timing, and duration of emissions).

In this specific case study, only one family (Roofing, Tightness, Framework, and Flashing) brought out a net benefit, with the 3 indicators below zero. This family, composed of many wooden materials, has the potential to reduce and even neutralize global climate change impacts. Neutralization of GHG emissions is one of the climate targets by and after 2050. This could be possible by extending the boundaries of the building system by incorporating for example sustainable forest management based on simulations of biogenic carbon flows. Furthermore, an interesting question is raised: with which forest management strategy could CO_2 emitted from the construction of a concrete building be compensated?

Dynamic climate indicators are the only ones to be able to consider the biogenic carbon influence. This feature, already acknowledged by the literature, makes dynamic LCA a powerful help for the management and mitigation of GHG emissions including the carbon capture.

We also conducted a sensitivity analysis of LCA results with respect to time-varying building parameters based on both conventional and dynamic metrics. Relevant lifecycle scenarios for the same case study were developed using collected parameters. This study shed light on the importance of specific dynamic processes encountered in the different lifecycle phases, such as system degradations and technological innovations. Globally, the identification of the most important scenarios does not differ significantly when using dynamic or conventional metrics, especially when biogenic carbon is not part of the LCI. However, when we need to establish long-term impact pathways with long-term technological change (e.g., end-of-life technologies) and with bio-based products (e.g., bio-bases insulation materials), dynamic LCA makes the scenario's performance clearer by evaluating when and how it affects the climate. One major finding from the case study is that dynamic LCA may inverse conclusions of conventional LCA for certain bio-based systems. The dynamic metrics illustrate the advantage of bio-based insulation material; on the other hand, bio-based energy production is not encouraged as a future alternative to the French energy mix. Yet, these conclusions are inversed within GWP metrics.

New metrics for decision making in the building sector

Finally, this work tried to bring responses to our fundamental research questions (Section 1.3): how and in which type of studies dynamic LCA could change the decisions with respect to conventional LCA. The tools proposed in this work can support decision making for appropriate strategies of GHG mitigation (e.g., identifying the hot spot, offering alternative solutions) at the different level of building actors: building design, eco-design of construction products, public policy. These tools emerge from our findings from the very first case study of dynamic LCA. A new ranking method to prioritize the mitigation actions was proposed and was applied to the 10 product families and prospective scenarios. Based on the case study, it has been shown that the new metric based on two-dimensional analysis (temperature peak and its timing) of each investigated element has effectively a potential to change rankings and then decision makings.

All the results and outcomes of the present work are based on the DyPLCA tool (models and databases). One of the assumptions was that future climate systems have the same response to emissions as today's one (in LCIA model, climate parameters characterizing the phenomena are considered constant). Meanwhile, if assuming that the severity of climate response to emissions changes over time, the result interpretation will be potentially different from current ones. This new assumption of an evolving model, sheds light, once again, on the importance of the emission timing.

6.2 Perspectives

The goal of future research is to consolidate the dynamic LCA methodology of buildings broadly by two distinct angles: 1) improvement of technical usability of dynamic LCA in the building sector for LCA practitioners, and 2) enhancement of the scientific research so that dynamic LCA can propose more effective tools for helping decision makings and for preparing future environmental regulations.

The first angle can be completed by the aspects below:

- *Development of building dynamics database*: Due to the limited time for the thesis work and to a lack of accessible data, it was necessary to reduce the research fields of time-varying building parameters of building systems. The enrichment of the database would help to perform dynamic LCA with more realistic assumptions, which will result in identifying the most influential parameters of the building systems. In consequent, it could simplify the dynamic LCI modelling of buildings. Also, a guide is necessary for the application of dynamic LCA to buildings.
- *Utilization of French EPD of construction products*: Until now, all our calculations of dynamic LCA have been based on Ecoinvent for the reason of the compatibility of LCI dataset with DyPLCA tool. The French building sector disposes of INIES database that gathers environmental impacts data of the construction products (EPD), which are provided directly by manufacturers in the framework of EN15804+A1 standard. Therefore, EPDs represent more reliable and accurate impact data (not LCI data) than those calculated with generic inventories like Ecoinvent. In order to make the best use of EPD of construction products and potentially to prepare future environmental regulations, it is important to enrich EPD with LCI data (at least emission flows) that are not included at this moment.
- *Simplification of temporalized LCI for the contributor of construction products:* For our case study, the time step of dynamic LCI calculation has been set to 1 day in order to obtain a precise temporal profile of emissions. It allows us to identify even emission flows during product fabrications processes at a certain point before the use of products. However, simulations using this time granulometry take a significant calculation time and may not always be necessary, for example, for climate change impacts and studies with a long-time scale as buildings. The sensitivity analysis of dynamic LCA results with respect to LCI time step showed that results with yearly time step LCI do not significantly differ from that with daily time step. In order to confirm this simplification, the

sensitivity analysis with different typology of buildings (that potentially have a different typology of GHG emissions) is necessary. Furthermore, it is important to investigate LCA result accuracy using LCI aggregated at the level of life cycle stages, because EPD is built at the level of building component (e.g., windows, not at the level of PVC and glazing). That means, using EPD (if we could know LCI data) losses dynamic consideration of the background system (e.g., emissions at a PVC fabrication phase would be invisible but aggregated at the level of window fabrication phase).

- *Development of other dynamic LCIA model*: an LCA is a methodology, so-called multi-criterion evaluation tool. In the building sector, 26 different impact categories are evaluated in conventional LCA. Besides climate change impact, dynamic LCIA models only exist for toxicity impacts. At this moment, we did not yet implement toxicity assessment in the case study due to considerable computation time. For further work, it is important to extend dynamic LCIA modelling to other categories, which are relevant in the context of a building system, such as the resources depletion (abiotic and fossil), water and air pollution, and ozone depletion.
- *Diminishing calculation time and memory use of dynamic LCI*: At this moment, the calculation time and memory usage for the case study were very important especially for dynamic LCI generation by DyPLCA web application. In order to make dynamic LCA more accessible by actors in the building sector, it is necessary to diminish calculation time and memory use. The first thing to be considered is the simplification of temporalized LCI as already raised above.

Concerning the second aspect, we can propose the following works to improve:

- *Integration of the short-term variability of household's energy consumption into dynamic LCA*: Contrarily to our proposition of LCI simplification, the contributor of energy consumption would be necessary to use small time step for LCI for certain types of buildings. Before the present thesis, Fouquet (2015) studied the influence of short-term variability of household's energy consumption on the environmental performances of buildings within the attributional LCA framework. For example, it was demonstrated that the hourly time step is required for a proper environmental assessment when taking into account the interaction between buildings with local production and the power grid. Contrarily, the difference between the annual average mix of electricity production and the hourly mix was not significant except for buildings equipped with an intelligent energy management system (e.g., demand response management system). For further work, it is thus interesting to couple this assumption of short-term dynamics of energy consumption with dynamic LCIA, but separately from the environmental assessment of the other contributors. In order to do that, the DES

- *Deepening the scientific understanding and more explicit definition of dynamic climate change impacts*: For most of LCA studies, climate change impacts have always been evaluated based on GWP metric. Meanwhile, in Section 5.2 of the present thesis, we tried to extend our discussion on the assessment of climate-related risks with at least two-dimensional analysis, i.e., temperature peak and its timing based on the IPCC (2018) report. Nevertheless, we do not yet know if the conventional metric can be replaced by the new metrics, or if both metrics can be complementarily used. Therefore, it is important to study comparatively their relevance, weaknesses, and advantages.
- *Uncertainty analysis in dynamic LCA:* Dynamic LCA enables to compute future emissions and impacts pathways by introducing temporal characteristics (time-varying parameters of building systems and temporal parameters that build production and supply chain). However, these temporal characteristics are themselves factors of results uncertainties. For further work, the uncertainty analysis of dynamic impacts results should be developed.
- *More case studies with different typology of buildings*: We conducted only one case study with a specific typology of the building (single house, based on wood). Now that the feasibility of dynamic LCA has been shown thanks to this case study, it is necessary to extend the application to other case studies with different typology of buildings and typical buildings in the French context. The iteration of dynamic LCA studies would enhance our findings related to dynamic climate change impacts and give more precisely helps for decision makings.
- *Application of dynamic LCA for the renovation strategy*: At this moment, we recommended to use dynamic LCA for the new building design because the reliable data of a case study was available in a very recent project (Observatory project). However, the dynamic LCA could also be beneficial for other issues, such as the establishment of a renovation strategy. The dynamic LCA study enables to estimate more accurately environmental impacts of future activities, thus necessarily related to renovations, by taking into account time lags of emissions. Therefore, it is important to perform dynamic LCA studies including renovation cases.

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Annex I

DyPLCA model and tool

I.1 Dynamic LCI model

Life cycle inventory (LCI) is the second step of LCA, involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO, 2006a; 2006b). The conventional LCA uses a matrix-based calculation for the construction of LCI where the system under study is considered as linear with respect to intermediary and elementary flows (in other words, elementary flows are proportional to intermediary flows). In DyPLCA, dynamic LCI calculation is based on a supply chain concept where physical relations exist between processes.

The LCI resolution is formulated by the matrix algebra approach closing a system in a linear space and the base equation for that is given by (Heijungs and Suh, 2002) as follows :

$$s = \boldsymbol{A^{-1}} * f \tag{1}$$

Where the matrix $\boldsymbol{A}$ gives a unitary physical relationship (exchanges between processes per unit), the vector s (this term is called *scaling vector*) gives to each production process their contribution of each supply in the entire system, the vector f represents the final demand (reference flow). Emission vector g is calculated by multiplying the matrix $\boldsymbol{B}$ of environmental interventions by vector s as follows:

$$g = \boldsymbol{B} * s = \boldsymbol{B} * \boldsymbol{A^{-1}} * f \tag{2}$$

The noteworthy point of the DyPLCA development is that the mathematical model of dynamic LCI preserves this formalism (which is the background of LCA method) at the level of total balances, but the connected processes are shifted in time resulting in disaggregated intermediary and elementary flows.

The temporal LCI model is composed of a process model and a supply model (Tiruta-Barna et al., 2016), their combination resulting in elementary flows distributed in time. The process model is composed of: (i) production functions $\alpha(t)$ and environmental intervention functions $\beta(t)$, which describe the process dynamics; and (ii) additional parameters functioning period T, and production period r. Supply model is characterized by parameters delay δ, and supply period (or frequency) τ. Besides, the start date of the analysis $t0$ is considered as time zero (corresponding to a calendar date), and is associated with the functional unit. The temporal parameters and functions are summarized in Table I-1.

Table I-1: Temporal parameters for dynamic LCI modelling

	Parameter	**Significance**
Process model	$\alpha(t)$ function	Production function (shape of activity through the time)
	$\beta(t)$ function	Environmental intervention function (shape of emissions or resource consumption through the time)
	r	Production period (time between the earliest input and the latest output of the activity)
	T	Functioning period (or a lifetime of the main infrastructure)
	$t0$	Start date of analysis
Supply model	δ	Delay (storage time, no activity takes place)
	τ	Supply period (supply frequency)

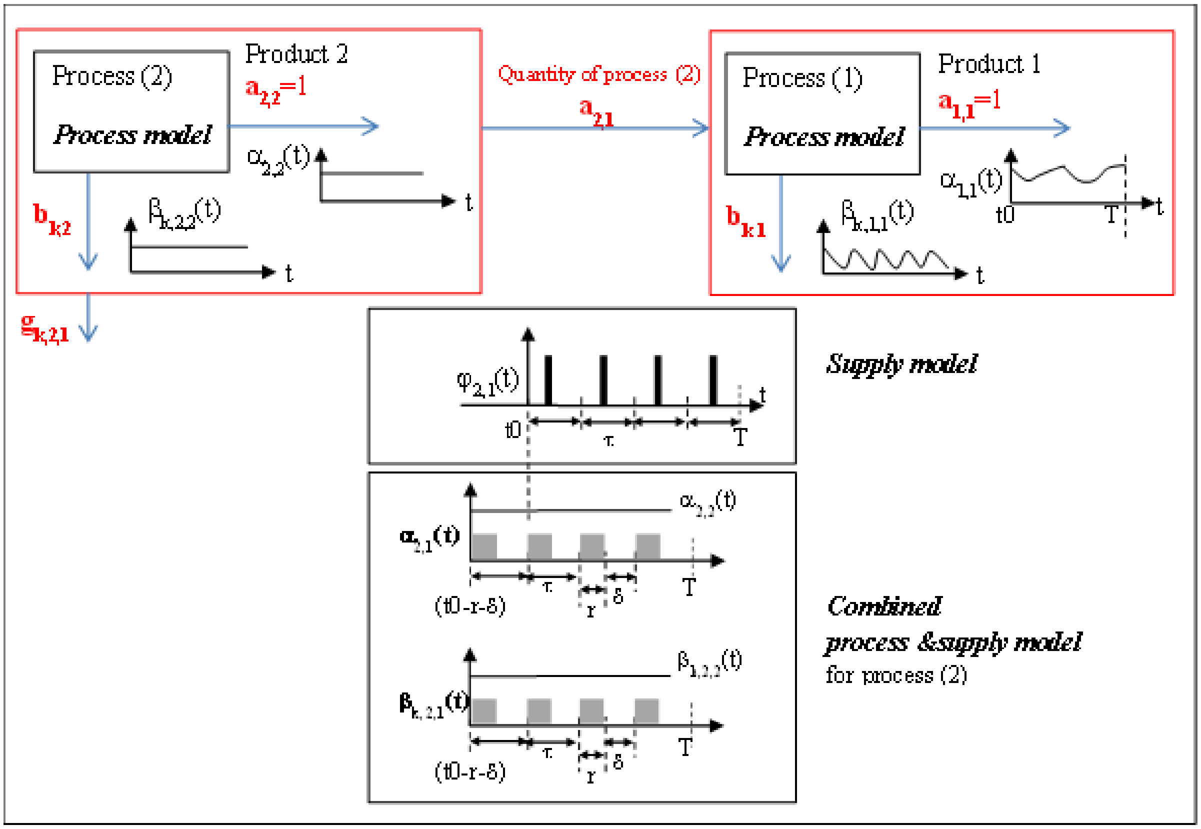

Figure I-1: Two subsequent processes: current ecoinvent inventory related data (in red); process model, supply model, and their combination. Legend for variables: $a_{i,j}$ and $b_{k,j}$: elements of matrix A and B (i, j are processes, k is an environmental intervention); $\alpha_{i,i}$ and $\beta_{k,i,i}$: production and emission functions for process i; T: functioning period for the system; t_0: evaluation's start time; δ: supply delay period; r: production period; τ: period of supply of product 2 for process 1; $\varphi_{2,1}$: supply function from 2 to 1; $\alpha_{2,1}$ and $\beta_{k,2,1}$: production and emission functions for process 2 working for process 1; $g_{k,2,1}$: quantity of k emitted by process 2 when working for process 1. From Tiruta-Barna et al. (2016).

The normalized functions α and β link the conventional inventory (equations 1 and 2) to the temporal model in the sense that the integral of these functions over the defined life time T of the process results in the inventory data $a_{i,i}$ in technology matrix A and $b_{k,i}$ in intervention matrix B:

$$a_{i,i} = \int_{t_0}^{t_0+T} \alpha_{i,i}(t)dt \tag{3}$$

$$b_{k,i} = \int_{t_0}^{t_0+T} \beta_{k,i,i}(t)dt \tag{4}$$

Where α(t) is a flow of product and is represented by the reference unit by time (e.g. $kg.h^{-1}$, $m^3.day^{-1}$, $kWh.s^{-1}$, etc.), β(t) is the flow of the environmental intervention k (e.g. $kg.year^{-1}$). The coefficients $a_{i,i}$ and $b_{k,i}$ are spread over time throughout the complete representative period (e.g. per life time for a wastewater treatment plant) based on the respective α and β functions.

On a supply chain, each producer functions during a certain period ($span_2$) determined by the demand from the consumer process. The consumer demands products from the technosphere during a certain period named $span_1$. As such, the functioning periods (span) are inter-dependent on the supply chain. Starting from the unit function period T_{uf} (with $span_{uf} = T_{uf}$) the span periods can be calculated by going upstream on a graph structure. The number of batches of product (2) delivered by process (2) to process (1) $\sigma_{2,1}$ is given by:

$$\sigma_{2,1} = \max\left(\left\lfloor\frac{span_1}{\tau_{2,1}}\right\rfloor, 1\right) \tag{5}$$

where $\sigma_{2,1} \geq 1$ is an integer. Consequently, the functioning duration of process (2) can be defined by:

$$span_1 = \tau_{2,1}(\sigma_{2,1} - 1) + r_2 \tag{6}$$

The supply chain model describes the schedule and quantity delivered of a producer process to a consumer. The intermediary flows between processes (equation 5) and environmental interventions flows (equation 6) are obtained through the following equations:

$$\alpha_{2,1}(t) = -\frac{s_1\, a_{2,1}}{C_2(t)}\, \alpha_{2,2}(t) \tag{7}$$

$$\beta_{k,2,1}(t) = -\frac{s_1\, a_{2,1}}{C_2(t)}\, \beta_{k,2,2}(t) \tag{8}$$

with s_i being elements of scaling (total output) vector s and C a capacity factor, defined by:

- for intermittent supply:

$$C_2(t) = \sigma_{2,1} \int_t^{t+r_2} \alpha_{2,2}(t)\, dt \tag{9}$$

- for continuous supply:

$$C_2 = a_{2,2} \frac{span_1}{T_2} \tag{10}$$

Besides the quantities of environmental interventions (values of β), the position in time of the activity (production and emission functions) is one of the key results of the model. Functions α and β of a producer process (process 2 in figure 2) are distributed in time starting from the zero time of the consumer process, i.e., from the beginning of the activity of process (1):

$\alpha_{2,1}(t) > 0$ and $\beta_{k,2,1}(t) > 0$

for $t \in \left[\left(t_{0,1} - r_2 - \delta_2 + \left(x_{2,1} - 1\right)\tau_{2,1}\right),\ \left(t_{0,1} - r_2 - \ \delta_2 + \left(x_{2,1} - 1\right)\tau_{2,1} + r_2\right)\right]$

with $x_{2,1} = 1, \dots, \sigma_{2,1}$

$\alpha_{2,1}(t) = 0$ and $\beta_{k,2,1}(t) = 0$ for t elsewhere (11)

In the case of continuous supply, the intervals become:

$$t \in \left[\left(t_{0,1} - r_2 - \delta_2\right),\ \left(t_{0,1} - r_2 - \ \delta_2 + span_1 + r_2\right)\right] \quad (12)$$

The continuous mode can also be considered as a supply of consecutive batches without pause, i.e., a delivery interval equal to the production period r (i.e., $\tau_{2,1} = r_2$).

The final objective of the model is to obtain the environmental interventions distributed over time, i.e., all β functions evaluated and scaled over the timeline. Their integration over time (between initial and final time values) yields the conventional inventory results, i.e. $g_{k,i,j}$ quantities for each substance *k* and process *i* linked to process *j*, and the total integrated environmental intervention g_k (over the full time span) of compound *k*:

$$g_{k,i,j} = \int_{t_{0,i}}^{t_{0,f}+T_f} \beta_{k,i,j}(t)\, dt \quad (13)$$

$$g_k = \sum_{i=1}^{m} \sum_{j=1}^{m} g_{k,i,j} \quad (14)$$

Then, these functions can be summed for a given substance k, in order to obtain the γ(t) function – its aggregated emission profile over the life cycle:

$$\gamma_k(t) = \sum_i \sum_j \beta_{k,i,j}(t) \quad (15)$$

Equation (14) allows the validation of the model by comparing the resulting g_k values with the corresponding elements of vector $\boldsymbol{g}$ in conventional LCA, for a given case study.

The adopted numerical resolution method combines the flow balance equations above and a graph-search algorithm on the network of processes which traces back in time (starting from t0 of unit function) the occurrence time of each process. It was implemented in an IT tool hosted on a server, with a web user interface.

I.2 DyPLCA web application

The web application tool of DyPLCA is available at http://dyplca.pigne.org. In this application, two types of process are defined: foreground processes (the new processes created by the user for modeling the product system) and background processes (existing processes in databases). In order to define the temporal parameters, a database was developed as one of the great achievement of the project. The development of this temporal database is based on ecoinvent dataset. By now, they collected temporal parameters for more than 14,000 processes of ecoinvent. As the DyPLCA web application is connected to the database, the default value of temporal parameters is automatically given by the database for the background processes. For the foreground processes, temporal parameters are defined by the user on the application interface.

Besides, there are also some numerical parameters to be defined for the simulation such as the start date of the functional unit, numerical precision, and threshold for search algorithm, time step size, and time limit backward of analysis. These parameters can be chosen by the user, and they influence the precision of results and the calculation time.

For a given case study, the flowing steps need to be performed:

- Modelling of the system in SimaPro and exporting the technology/environmental interventions matrix
- Importing this matrix into DyPLCA tool
- Defining temporal parameters for the foreground processes if they are new, defined by the user
- Calculation of dynamic LCI
- Exporting the results

The DyPLCA web application tool provides as results three matrixes: *Beta matrix*, which represents the temporal behavior per environmental interventions; *Gamma matrix*, which provides the aggregated environmental interventions, i.e. gamma functions over the time for each type of chemical substances; and *Matrix H*, which represents the total emissions by process, without time dependency, in order to obtain a total balance (to be compared with those obtained from the matrix formalism – equations 1 and 2). *Beta* and *Gamma* matrixes can be then used for impact calculation.

Annex II

Supplementary information for Chapter 3

Table II-1: List of all collected time-varying building parameters

Parameter type	Dynamic aspect	Dynamic properties or characteristics varying over time
Building technology	Degradation of physical characteristics of a material	Thermal, chemical, mechanical performance of construction products and materials
	Degradation of equipment performance	Energy efficiency of the system, leaking
	Function evolution	Functionality of building: commercial, residential
End-user	Use evolution	Changes in building functionality
	User characteristics	Typology of tenant
	User behavior	Typology of occupation mode
Building technology / External system	Technological evolution	Recycling technologies development, innovation of materials and equipment Energy efficiency at product fabrication phase
External system	Electricity mix evolution	Future rate of the part of renewable energy production
	Regulatory changes	Political laws and regulations regarding the construction sector and building performance
	Climate change and its effect on local meteorology	Temperature, humidity, precipitation, etc.
	Pollution evolution	Substance reaction to environmental compartments
	Infrastructure evolution	Transport technology, energy network
	Logistic evolution	Production time, stocking time, transport time

II.1 Technological degradation

The durability of a system or a product and the temporal evolution of its technical performances can be estimated by knowing the underlying factors of system degradations. Degradation of construction products are characterized as technical failure or dysfunction at the level of material, products or components, and affects the functionalities of the global system. Numerous degradation models have been widely studied in different industries and academia of the building and construction sector. Talon (2006) for example developed a theoretical model to estimate the service lifetime of construction products by identifying their degradation phenomena. According to her study, the scenario of the temporal behavior of a product is defined as a chain of phenomenon (degradation mode, causes, consequences, and affected components). Her works allowed for a systemic estimation of multi-performance durability and one original and theoretical model that identifies the degradation phenomena has adapted to the construction products.

Deterioration of building components takes various forms (e.g., fissure and settlement of inert products, corrosion of metallic products, deformation of materials). This dynamic behavior is involved in the amount of material and energy flows in the average and long time scale. The performance degradation of the component, on the one hand, may lead to an increase in energy consumption (energy flows) and, on the other hand, requires a replacement of the equipment (material flows). In consequence, environmental flows associated with material and energy flows have time-variable profiles. The temporal evolution of technical performances through the lifecycle of a system studied can be modeled by system degradation rate, maintenance rate, replacement, and renovation. Figure II-1 describes conceptually the temporal evolution of technical performance levels with some typical operations during a building use phase that allows to keep or improve their technical performances until the end of a building life to satisfy a minimum requirement of the functional unit of construction products (Talon, 2006).

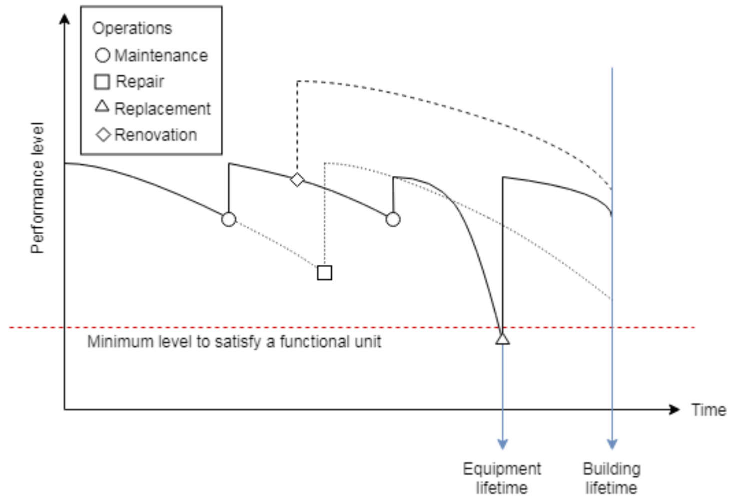

Figure II-1: Temporal profile of performance level of construction product and equipment (adjusted from (Talon, 2006))

Windows degradation

Windows present multiple functions such as thermal, acoustic, and mechanical (open and close for the air ventilation) performances. Also, it is important to ensure lightening building interior, health and thermal comfort level (Raj, 2017).

On the contrary, it represents at the same time an important source of heat loss of the building (ADEME, 2011). According to Olivia and Courgey (2010), the heat loss through the windows takes more and more an important part of the total heat loss, varying from 11% (very low energy performance building) to 25% (very high energy performance). The dysfunction of the window system can be observed at a different level of a component such as glazing, structural frame, spacers, and coatings (Talon, 2006). The lack of careful maintenance or climatic conditions leads to frequent replacement of some specific part of the window or a whole window. Consequently, additional energy consumptions compared to the initial system where any degradation does not happen, and additional material flows should be modeled in environmental assessments.

In the literature, we found some LCA studies that take into account assumptions about the technical performance of windows, service lifetime of sealant and hardware replacement. Carlisle and Friedlander, (2016) presents their assumptions regarding the replacement of windows elements for three scenarios: warranty with no maintenance or low maintenance rate, and two maintenance scenarios (low and high) with window frame replacement. The second reference is a report prepared for the Australian government concerning the service lifetime of windows (Howard et al., 2007). They also conducted a comparative LCA for the different types of windows available in the market: timber, aluminum-timber, aluminum and Polyvinyl chloride (PVC) – frames). Both studies estimated the service lifetime of windows based on maintenance rate.

Example of application to LCI modelling

For the application of time-varying parameters to LCI calculation, we can estimate material and energy balances related to windows with consideration of time-varying maintenance rate. This fact provokes the change in several replacements. This implies the modification of reference flows of a system.

Table II-2 synthesizes our bibliography analysis and retrieved data (lifetime of windows components and thermal performance). These data will be then used for LCI modelling to quantify the number of the replacement of windows and to estimate household's heat load over the lifetime of a building.

HVAC equipment degradation

The degradation of technical performances of HVAC systems appears as the dysfunction of systems and the degradation of energy efficiency that progressively increases the heat load for the following years. The regular maintenance of HVAC systems and occupant behaviors are important factors to maintain the initial performance level. Hereafter, we introduce our bibliography analysis of the technical performances degradation of the heat pumps, gas boiler, solar water heating system, air conditioning system, and electric heater. For each element, modifiable parameters over time are studied, and it is explained how to proceed to the integration of these parameters into dynamic LCA.

Eleftheriadis and Hamdy (2018) have performed simulations to estimate the energy consumption increase due to the degradation of the envelope and the energy equipment. Their results show that, depending on maintenance and selected heating system, after 20 years of exploitation, the building can consume between 18.4% and 47.1% more primary energy compared to a scenario in which no degradation was taking into account. Waddicor et al. (2016) used a building energy performance simulation to study the impact of predicted climate warming in addition to the energy efficiency degradation due to the building aging for a library in Turin, Italy. They found out that degradation is not negligible. Magnuson (2013) assessed the energy use of a building, and he integrated equipment degradation into the analysis. The author concluded that, with degradation, the global energy consumption of a building increased by 15% and, particularly for the electrical HVAC equipment, the increase in energy consumption was 27.3% over the equipment lifespan.

Some reports present the degradation of HVAC equipment in function of age. For example, Hendron (2006) provides a set of guidelines for estimating the energy savings that can be achieved by good practices and maintenance. The author gathers data on HVAC equipment system efficiency and degradation. Collected time-varying parameters for electric HVAC equipment efficiency are c*oefficient of performance (COP), energy efficiency ratio (EER), seasonal energy efficiency ratio (SEER)* and *heating seasonal performance factor (HSPF)*. When the equipment is fuel sourced, other ratios and indicators can be used, such as *annual fuel utilization efficiency (AFUE).* Besides, one study introduces a new indicator of *annual system performance factor (ASPF)*. The definitions of each term are the followings:

- *COP* is typically used for heat pumps, and it measured how much heat the heat pump creates using one watt of electricity. Thus, it is defined as the ratio between the thermal energy restituted from heat pumps systems and the energy provided to make HVAC equipment functioning, i.e., energy provided to compressor, pump, evaporator, and condenser.
- *EER* is the ratio of cooling output to the energy in order to operate the system. EER is typically measured at fixed horizon indoor (80°F) and outdoor (95°F) conditions.
- *SEER* is a measurement of the total heat removed from space during the annual cooling season divided by electric energy consumed in watts-per-hours. This parameter is designed to account for typical variations in outdoor temperature during the year.
- *HSPF* is used to measure the cold-season performance of electric heat pumps. It is the ratio of heat output during the heating season to energy input.

Examples of application to LCI modelling

Energy consumption by heat pump can be calculated using a dynamic energy simulation tool, e.g., COMETH, in taking into account the maintenance rate scenario to estimate COP for given years. Figure II-2 illustrates an example of the degradation rate of COP following the years with respect to the initial year estimated by the maintenance models of Griffth et al., (2008). This assumption of technical performance evolution of heat pump resulting finally in the evolution of energy consumption deals with the change in reference flow.

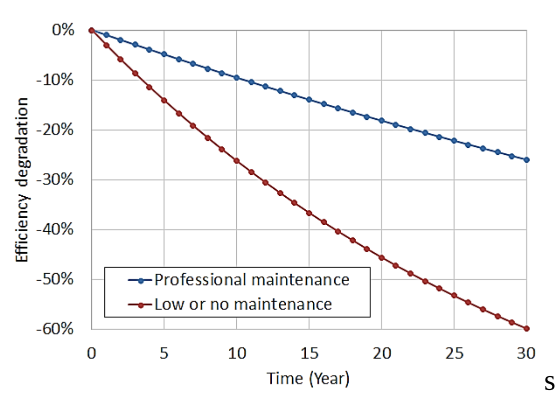

*Figure II-2: Degradation rate of COP of a heat pump with two maintenance scenarios (Professional maintenance, Low or no maintenance) calculated by the mathematical formula (COP(t) = COP(t-1)*maintenance rate) of Griffth et al., (2008)*

Table II-2 synthesizes collected data of loss of energy efficiency for investigated HVAC equipment. These data will be then used for DES to obtain household's energy consumptions for given years that will be integrated into LCI modelling.

Photovoltaic panels degradation

Despite the lack of measured performance data, there is an increase in the perception of the need to consider system degradation in the evaluations of energy and economical PV systems performance (Kneifel et al.).

There are multiple technologies regarding PV panels nowadays, and there is an increasing interest to develop more efficient panels in terms of conversion factors and cost. A PV panel is constituted by PV modules, which are composed of PV cells. A PV system is a combination of panels installed in a unit. The PV cells have evolved through time.

First generation cells are the crystalline silicon (Si) wafers (mono-crystalline, polycrystalline, ribbon-Silicon). They are thin cells (0.15 to 0.2 mm), connected in series and encapsulated under protective glass. Despite their elevated cost, they represent more than 85% of modules installed worldwide. Their average lifespan is 25 years, and the conversion efficiency is between 13 and 15% for polycrystalline and higher than 18% for mono-crystalline.

Second generation cells are the thin layers (amorphous Silicon, cadmium telluride [CdTe], indium copper and indium diselenide [CIS or CIGS]). They are made by the very thin layer (of a few thousandths of mm) of single semiconductor materials (amorphous and crystalline silicon pc-Si) or compound (copper-indium-gallium-selenium CIGSe (CuInGaSe), cadmium telluride CdTe, organic-based polymers or small molecules, hybrid dyes (DSSC) or perovskite). For amorphous silicon, for example, the conversion efficiency is between 6 and 9%.

The third generation of PV cells aims to increase drastically the conversion efficiency while reducing the cost by a factor of 2 to 3. To reach these very high conversion efficiencies, the photovoltaic components must reduce optical and electrical losses. For that, the research community has studied new materials, such as specific nanomaterial and organic molecules with the needed properties (Roux, 2013). The fourth generation is represented by multi-junction concentrator cells: the film layers can capture solar energy in different parts of the Sun's spectrum. Their cost is still too high. However, they still present a higher efficiency compared to the other generations.

The degradation rate may vary with the PV cell technology. For this reason, we focus on the data collection in the following technologies: mono-Si, poly-Si, amorphous-Si, CIS, CdTe.

II.2 Technological innovation

In the long lifetime of a building system, there is not only the system degradations but also technological innovations that improve the technical performances of buildings. Accounting for not only the degradation of a system but also the upgrade of a system through technological innovation allows the successful strategy development to reduce environmental impacts of the building system further. The integration of prospective scenarios of different industrial sectors into LCA has been effectuated in academic researches (Spielmann et al., 2005; Pehnt, 2006; Shimako, 2017).

Meanwhile, there is no consensual method for prospective LCA and prospective studies in general. Some researchers attempted to resume scenarios in various typologies that are defined in the function of their objectives (Börjeson et al., 2006; Hussain et al., 2017). According to these studies, the typology can be differentiated by different measures such as economy, policy, technology, demography, etc. It is thus important to clearly define the objectives of the prospective study that indicates why the dynamic LCA applied to the building sector should be considered as potential scenarios.

Two primary objectives of the prospective scenario integration into our building LCA can be raised:

- Prediction of future possible impact pathways of a building system based on existing technological innovation scenarios

- Development of future GHG reduction strategies identifying roles of the building sector

Equipment and construction products are replaced at least several times over the building lifetime. The replacement frequency varies according to their service lifetime in a range from several years (e.g., painting materials) to several decades (e.g., insulation materials, windows, energy equipment). The infrastructure or energy generation system will also be altered by other innovative solution after their long service lifetime. The replacement at average and long term interval necessarily involves technological innovations for certain equipment (Frijia et al., 2012) and there can be various possible technological innovation pathways with respect to the environmental impacts.

Designing technological advancements into building LCA study requires the prospective strategy study of economy and policy for different industrial sectors. Today, these strategies for any technological change need to be consensually realized with respect to environmental issues.

Therefore, it is important to perform the building environmental assessment with national or international directives for the construction sector sustainable development in the context of the reduction of GHG emission. The data collection of innovation scenarios for construction products was realized for the use of recycled material (e.g., window glazing, glass wool), insulation material, painting material for the moment.

Insulation product innovation

As stated in Section 3.2.2, building envelops are an important source of heating and cooling energy loss. Keeping this fact in mind, preventing energy losses from leakage and maximizing the efficiency of heating and cooling system are deemed an important as the European strategy is to meet energy consumption and GHG emission common goal (European Commission, 2016). In order to overcome the problem of energy loss, the reduction of thermal conductivity and the increase in material's thickness can be considered as a solution as proved in Equation 3-1 and 3-2 in Section 3.3.1. Ceteris paribus, the increase in thickness means making living space narrower, increasing the material quantity and environmental impacts as well. For that reason, producing insulation materials having a low thermal conductivity comes to be an ideal solution. It enables the application of thin building envelops with high thermal performance, low environmental impacts, and low cost for building designs. The European Commission has been financially supporting the development of such high insulation performance (Pantazaras, 2013; "Horizon 2020," 2019)

Besides, significant efforts by insulation industry research and development have been conducted to improve the thermal performance of insulation materials (Jelle, 2011; Boafo et al., 2014). Vacuum insulation panels (VIP) and aerogels are the two most promising materials as they present lower thermal conductivity than conventional materials (Quenard, 2017). We found several studies that present the thermal conductivity values of high-performance insulations and their degradation over time (Berardi and Nosrati, 2018; Jelle, 2011; Schwab et al., 2005). They highlight the following materials as tomorrow's high-performance ones: *vacuum insulation materials (VIM), nano insulation materials (NIM), dynamic insulation materials (DIM)*, and *NanoCon*. The thermal conductivity of most of these new materials is estimated to be inferior to 4 mW/(m.K) that is very low compared to the conventional materials, presented in Figure II-2. By now, there is only one specific EPD regarding a VIP in the INES data set with no inventory data associated. Due to the lack of inventory data, the assumption of the environmental performance of these innovative insulations is not yet able to be implemented in dynamic LCA.

Today, we can find on the market renewable insulation materials and insulating products with increasing recycled content, in line with circular economy development. And, some of their LCI models are existing in ecoivnent datasets such as cork slab, wood wool, EPS 20% recycled, EPS with 100% recycled content and glass wool with 80% of recycled content). Therefore, we consider them as the representatives of innovating insulation materials for our prospective LCA study, described in Section 4.5.3.

The innovation of waste treatment technology

In Section 3.3.2, we have seen that the building and construction sector plays an important role in reducing wastes and increasing the recycling rate in France. In 2014, the sector produced a considerable amount of inert waste materials (e.g., concrete): 31.5 Mt, non-danger materials (e.g., plastic): 9.7 Mt, and dangerous materials from the construction and demolition activities: 1.1 Mt (ADEME, 2018). These wastes are in general treated as disposed of materials and products, and send to a center for the stock or landfill processing. It requires considerable land use and generates emissions into the soil and water. Also, the landfill of materials generates methane through the chemical and biological processes (Barlaz et al., 2009).

In this context, our concern about waste treatment is the shift from a closed life cycle of materials and products to a circular-based approach of economic activities related to the building (ADEME, 2018; "Horizon 2020," 2019). There is the non-negligible potential of the valorization of materials and energy recovering through end-of-life scenarios. To implement the products recycling scenario in a dynamic study, we collected first the actual valorization (recycling, energy recovery) rates focusing on some materials of the construction sector (inert materials, wood products, insulation materials, plasterboard) and their future ones when data is available. Besides, we also conducted research for scenarios of the collection of waste materials. According to the ADEME's report of the French recycling evolution (Nicolas 2017), the five principal industrial sectors in terms of the building construction (ferrous metal, non-ferrous metal, paper and paperboard, glass, and plastic) has constantly shown the diminution of their production since 2005. At the same time, we have observed the positive evolution of the materials waste collection rate except for the ferrous metal sector. Figure II-3 shows some examples of collected data.

Example of application to LCI

In ecoinvent dataset, there is no available LCI process of recycling model specific to the French context. However, generic LCI models of material recycling were created in the frame of MDEGD project (MEEM and MLHD, 2016). Thanks to this source process, we can consider a mixed scenario of different waste treatment (e.g., landfill + incineration + recycling) as illustrated in Figure II-3.

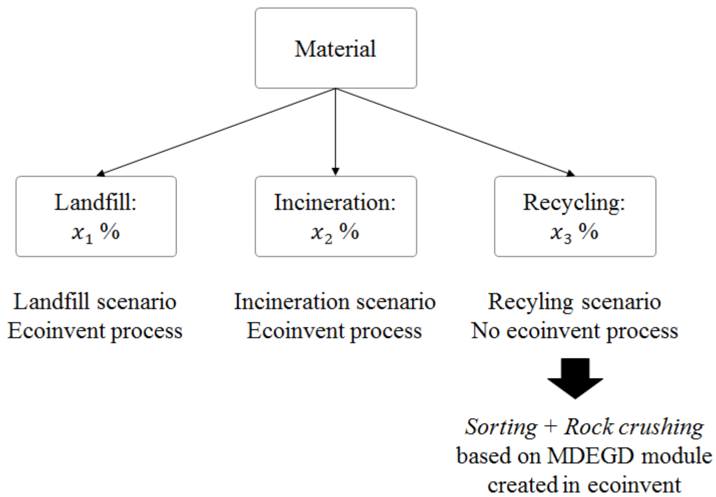

Figure II-3: Illustration of the mix of different waste treatment scenarios with recycling LCI model based on MDEGD project (MEEM and MLHD, 2016)

Table II-2: Collected data and models of time-varying parameters listed in Table II-1

Concerned products/materials	Dynamic aspects/properties	Data collection method	Collected data / model	Source	Remark
Expanded Polystyrene (EPS)	Decrease in heat transfer rate	Measurement / Experimentation	Decrease by 25% / 20 years (0.50 to 0.55 W/m².K in 1987 0.38 to 0.41 W/m².K in 2007)	(Stazi et al., 2009)	• This is an experimental study effectuated to insulation materials retrieved from an existing building constructed in the 1970s • Decrease rate varies in function of the side of envelop
Glass wool	Increase in thermal conductivity	Measurement / Experimentation	Increase by 12% / 25 years	(Stazi et al., 2014)	• This is an experimental study effectuated to insulation materials retrieved from an existing building constructed in the 1980s • The decrease of the hydrophobicity of the glass wool is the main cause of thermal conductivity increase
Polyurethane (PU)	Decrease in thermal resistance	Measurement	Decrease by 6%/100 first days Decrease by 20%/1000 first days Decrease by 27%/5000 first days	(Choi et al., 2017)	• This study evaluated the degradation of different types of polystyrene insulation.
Window	Thermal performance degradation/gas leakage	Technical lifetime	Glazing seals: 5 years Glazing putty: 15 years	(Howard et al., 2007)	• Air leakage might take the internal temperature outside of the comfortable temperature range • Glazing seals and glazing putty should be replaced to maintain air leakage performance

					• Hardware slowly degrades and losses functionality
Window with a frame of: - Wood - PVC - Aluminum - Aluminum-clad wood	Service life/maintenance rate	Scenario with maintenance model (RS Means, 2013)	Wood-framed window (e.g.) 20 years with no maintenance 30 years with low maintenance +80 years: with high maintenance	(Carlisle and Friedlander, 2016	• The lifetime of windows varies in function of the maintenance rate (no, low or high maintenance) • Service life was retrieved from a life cycle costing database (RS Means, 2013)
Window	Thermal performance degradation/gas leakage	Measurement / experimentation	5% of argon gas at most is escaped through 25 years, which corresponds to the thermal resistance decrease by 0.04 W/m².K	NF EN 1279-3 / 2003 - Annex B	• New glazing is presenting, at time zero, a leakage rate less than 1% / year with the leakage rate doubled at every decade • The Annex B of the Standard NF EN 1279-3 presents comparative data for Argon leakage between the real and artificial windows
Heat Pump	COP decrease / maintenance rate	Mathematical model	COP decrease: High maintenance: 0.25% / year Low maintenance: 1% / year	(Griffth et al., 2008)	• According to the authors, these rates are assumptions, and further research is needed to understand better how to model this phenomenon.
Air Conditioning system	Cooling system efficiency decrease	Measurement	-7% in the first year -5% in the second year -2% in the following years until 30% of efficiency loss, then it remains constant.	(Power Knot, 2017)	• Loss of performance will continue to accumulate until the balance is achieved. Usually, the degradation of effectiveness remains between 20% and 30%.

Gas boiler	AFUE decrease / maintenance rate	Mathematical model	$AFUE(t) = AFUE_{initial} \times (1-M)^t$	(Hendron, 2006)	• M values (maintenance factor) for all technologies are presented in the report • $AFUE_{initial}$ for the AFUE at year 0 and M for maintenance factor
Solar water heating system	Water heater efficiency decrease	Mathematical model	$EF(t) = EF_{initial} \times (1-M)^t$	(Hendron, 2006)	• EF is the energy factor of the water heater. • $EF_{initial}$ for the EF at year 0 and M for maintenance factor
Photovoltaic system	Degradation of PV module/performance degradation	Statistics from field measurements	PV module performance degradation: - Average: -0.8%/year - Median: -0.5%/year	(C. Jordan and R. Kurtz, 2013)	• The document gathers the degradation rates reported worldwide over 40 years • 1920 sample data was collected
Photovoltaic system	Degradation of PV module/service lifetime degradation	Statistics from field measurements	PV module lifetime in fucntion of degradation rate: - 0.43%/year: 20 years - 0.46%/year: 10 to 20 years - 0.71%/year: 0 to 10 years	(C. Jordan and R. Kurtz, 2013)	• Correlation between degradation rate and PV module lifetime is statistically shown •
Vacuum Insulation Panels with laminated Al foil (VIP-AF) and VIP with Al-coated multilayer foils (VIP-MF)	Increase in thermal conductivity	Mathematical model	Initial value: 4 mW/(m.K) At 25th year: - VIP-AF: 4.5mW/(m.K) - VIP-MF: 8 mW/(m.K)	(Schwab et al. 2005)	• The increase in thermal conductivity with time is estimated in function of the increase in air pressure and water content in the VIP • No LCI data is available

Aerogel	Increase in thermal conductivity	Technical data from the product documents	Initial value: 13 mW/(m.K) No substantial change over time is obtained	(Jelle 2011)	• The variation of the thermal conductivity of the aerogel over time is not substantial (The value was retrieved in 2008) • No LCI data is available
Aerogel (roll)	Increase in thermal conductivity	Experimentation	Initial value: 18 mW/(m.K) At 25th year: 19.5 W/(m.K)	(Berardi and Nosrati 2018)	• The evolution of thermal conductivity is obtained with the experimentation varying the humidity, temperature and UV radiation • No LCI data is available
NIM, DIM, and NanoCon	Increase in thermal conductivity	Mathematical model	Initial value: < 4 mW/(m.K)	(Jelle 2011)	• Even though large challenges will still be necessary to invent these materials, the authors considered that they would be undeniable for future alternatives of thermal insulation materials • No LCI data is available
Expanded polystyrene (EPS)	Valorization rate of material	Measurement	Rate of waste treatment - 54%: recycling - 9%: energy recovery	(EcoPSE, 2014)	• 80% of recycled material is recovered as polystyrene granules that can be used as plastic material, 20% is reintegrated in EPS production
Wood	Valorization rate of material	Measurement / Scenario prospective	- 2015: material recovery: 43%, energy recovery: 34%, landfill: 23% - 2025 : material recovery: 68%, energy recovery: 18%, landfill: 14%	(ADEME, 2015)	• ADEME developed two prospective scenarios for the horizon of 2025: 1) scenario prioritizing the material recovery and 2) scenario prioritizing the energy recovery • The values in this table are for the scenario of material recovery

Flat glass	Collection of waste	Scenario prospective / National strategy	Rate of collection - Current: 5% - 2020: 20% - 2025: 40%	(MTES and MEF 2017)	• The “green deal” regarding flat glass presents low and mid-term goals for increasing the flat glass collection
Inert material	Valorization rate of material / Collection of waste	Scenario prospective / National strategy	Valorization rate - 2012: 60% - 2020: 70% Quantity of collection - 2014: 20 million tons - 2020: 30 million tons	(MEEM and MEIN, 2016c)	• The valorization rate includes both material and energy recovery

Annex III

Supplementary information for Chapter 4

Table III-1: List of all GHGs considered in the case study (exported from the matrix of environmental interventions of the system modelled in Simapro)

	substance	Compartment	Sub-compartment
1	Carbon dioxide, in air	Raw	in air
2	Carbon dioxide	Air	
3	Carbon dioxide, biogenic	Air	high. pop.
4	Carbon dioxide, biogenic	Air	low. pop.
5	Carbon dioxide, biogenic	Air	
6	Carbon dioxide, fossil	Air	stratosphere + troposphere
7	Carbon dioxide, fossil	Air	high. pop.
8	Carbon dioxide, fossil	Air	low. pop.
9	Carbon dioxide, fossil	Air	
10	Carbon dioxide, land transformation	Air	low. pop.
11	Carbon dioxide, land transformation	Air	
12	Carbon monoxide, biogenic	Air	high. pop.
13	Carbon monoxide, biogenic	Air	low. pop.
14	Carbon monoxide, biogenic	Air	
15	Carbon monoxide, fossil	Air	stratosphere + troposphere
16	Carbon monoxide, fossil	Air	high. pop.
17	Carbon monoxide, fossil	Air	low. pop.
18	Carbon monoxide, fossil	Air	
19	Carbon monoxide, land transformation	Air	low. pop.
20	Chloroform	Air	high. pop.
21	Chloroform	Air	low. pop.
22	Chloroform	Air	
23	Dinitrogen monoxide	Air	stratosphere + troposphere
24	Dinitrogen monoxide	Air	high. pop.

25	Dinitrogen monoxide	Air	low. pop., long-term
26	Dinitrogen monoxide	Air	low. pop.
27	Dinitrogen monoxide	Air	
28	Ethane	Air	high. pop.
29	Ethane	Air	low. pop.
30	Ethane	Air	
31	Ethane, 1,1-difluoro-, HFC-152a	Air	high. pop.
32	Ethane, 1,1-difluoro-, HFC-152a	Air	low. pop.
33	Ethane, 1,1,1-trichloro-, HCFC-140	Air	low. pop.
34	Ethane, 1,1,1-trichloro-, HCFC-140	Air	
35	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	high. pop.
36	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	low. pop.
37	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	
38	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	high. pop.
39	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	low. pop., long-term
40	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	
41	Ethane, 1,2-dichloro-	Air	high. pop.
42	Ethane, 1,2-dichloro-	Air	low. pop.
43	Ethane, 1,2-dichloro-	Air	
44	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	low. pop.
45	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	
46	Ethane, hexafluoro-, HFC-116	Air	high. pop.
47	Ethane, hexafluoro-, HFC-116	Air	
48	Methane	Air	high. pop.
49	Methane, biogenic	Air	high. pop.
50	Methane, biogenic	Air	low. pop.
51	Methane, biogenic	Air	
52	Methane, bromo-, Halon 1001	Air	
53	Methane, bromochlorodifluoro-, Halon 1211	Air	low. pop.
54	Methane, bromotrifluoro-, Halon 1301	Air	high. pop.
55	Methane, bromotrifluoro-, Halon 1301	Air	low. pop.
56	Methane, chlorodifluoro-, HCFC-22	Air	high. pop.

57	Methane, chlorodifluoro-, HCFC-22	Air	low. pop.
58	Methane, chlorodifluoro-, HCFC-22	Air	
59	Methane, dichloro-, HCC-30	Air	high. pop.
60	Methane, dichloro-, HCC-30	Air	low. pop.
61	Methane, dichloro-, HCC-30	Air	
62	Methane, dichlorodifluoro-, CFC-12	Air	high. pop.
63	Methane, dichlorodifluoro-, CFC-12	Air	low. pop.
64	Methane, dichlorodifluoro-, CFC-12	Air	
65	Methane, dichlorofluoro-, HCFC-21	Air	high. pop.
66	Methane, fossil	Air	stratosphere + troposphere
67	Methane, fossil	Air	high. pop.
68	Methane, fossil	Air	low. pop.
69	Methane, fossil	Air	
70	Methane, land transformation	Air	low. pop.
71	Methane, monochloro-, R-40	Air	low. pop.
72	Methane, tetrachloro-, CFC-10	Air	high. pop.
73	Methane, tetrachloro-, CFC-10	Air	
74	Methane, tetrafluoro-, CFC-14	Air	high. pop.
75	Methane, tetrafluoro-, CFC-14	Air	
76	Methane, trichlorofluoro-, CFC-11	Air	high. pop.
77	Methane, trifluoro-, HFC-23	Air	high. pop.
78	Nitrogen fluoride	Air	high. pop.
79	Sulfur hexafluoride	Air	high. pop.
80	Sulfur hexafluoride	Air	low. pop.
81	Sulfur hexafluoride	Air	

Table III-2: List of construction products of the testbed building (with English translation)

ELODIE name (in French)	Translation for English	Is it included?
1. Voirie et Reseaux Divers	**1. Highways and miscellaneous external works**	
1.1 Reseaux	**1.1 Networks**	
Bordure et Caniveau en béton	Kerb channel	No
Système de drainage en PVC [DN=125mm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	PVC draining system	No
Regard de visite en béton pour réseaux d'évacuation et d'assainissement en béton - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Manhole in concrete	Yes
Réseaux d'évacuation et d'assainissement en PVC - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Drainage and sewage networks	Yes
Gaines et fourreaux en PVC [DN=200mm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Pipes and shafts in PVC	No
Réseaux d'adduction d'eau en PVC - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Network water supply	No
1.3 Voirie, revetement, cloture	**1.2 Highways, claddings, coverings**	
Clôture en bois [haut. 2,4m] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Wooden fence	Yes
Bordure et Caniveau en béton	Kerb channel	No
Voirie et revêtements extérieurs en enrobés - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Exterior cladding	Yes
Dalle de voirie en béton	Concrete slab for road network	Yes
Pavé de Voirie en Béton	Concrete paving block	Yes
2. Fondations et Infrastructures	**2. Foundations and Infrastructures**	
2.1 Fondations	**2.1 Foundations**	
Béton de propreté dosé à 150 kg de ciment - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Bedding concrete	Yes

Bloc de coffrage en béton - sans béton de remplissage	Concrete shuttering block	Yes
Prédalle en béton armé	Precast reinforced concrete slab	Yes
2.2 Murs et structures enterrées	**2.2 Walls and Buried structures**	
Enduits extérieurs de peinture en pâte	External rendering	No
Enduit bitumineux pour l'étanchéité et l'imperméabilisation pour murs enterrés - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Bituminous coat for waterproofing	No
Mur extérieur de 18 cm d'épaisseur en Béton armé C25/30 XC4/XF1 CEM II/A-L	Exterior wall in reinforced concrete	Yes
Membrane synthétique pour l'étanchéité et l'imperméabilisation pour murs enterrés [ép. 2mm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Waterproofing synthetic membrane	Yes
3. Superstructure & Maçonerie	**3. Superstructure and Masonry**	
3.1 Elements horizontaux _ Planchers, dalles, balcons	**3.1 Horizontal elements - Floors, slabs, balcony**	
panneau semi rigide en laine de verre ISOCONFORT 35 épaisseur 240 mm	Glass wool	Yes
Plancher d'étage par solivage bois pour bâtiment tertiaire hors ERP	Wooden floor	Yes
Chapes / chapes flottantes en béton et mortier à base de ciment - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Floating screed and mortar, in concrete	Yes
DOMISOL LR 30 mm	Rock wool	Yes
Isoconfort 35 60	Glass wool	Yes
3.2 Elements horizontaux _ Poutres	**3.2 Horizontal elements - Beams**	
-	-	-
3.3 Elements verticaux - Façades	**3.3 Vertical elements - Façades**	
Mur ossature bois de montant 145 mm avec un entraxe de 60 cm non isolé, fabriqué en France	Wall, timber frame	Yes
Membrane d'étanchéité synthétique fixée mécaniquement	Waterproofing synthetic membrane	Yes

Isoconfort 32 Revêtu Kraft 200	Glass wool	Yes
3.4 Elements verticaux - Refends	**3.4 Vertical elements - Splitting**	
Isoconfort 32 100	Glass wool	Yes
Mur ossature bois de montant 145 mm avec un entraxe de 60 cm non isolé, fabriqué en France	Wall, timber frame	Yes
3.5 Elements verticaux - Poteaux	**3.5 Vertical elements - Columns**	
-	-	-
3.6 Escaliers et rampes	**3.6 Staircase and ladders**	
Escaliers et garde-corps associés en feuillus européens	Staircase in hardwood	No
Escaliers et garde-corps associés en résineux européens	Staircase in softwood	No
4. Couverture - Etaicheité - Charpente - Zinguerie	**4. Roofing, Tightness, Framework, Flashing**	
4.1 Toitures terrasses	**4.1 Flat roofs**	
Réseau d'évacuation et d'assainissement en polypropylène [DN=110mm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Drainage and sewage networks in PP	Non
Plaque métallique pour couverture en acier prélaqué	Metallic sheet for cladding, in precoated steel	Yes
Membrane synthétique pour étanchéité de toiture - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Waterproofing synthetic membrane	Yes
4.2 Toitures en pente	**4.2 Gable roofs**	
Charpente en résineux (douglas, sapin, épicéa) traité pour un usage de classe 2	Resinous frame	Yes
Isoconfort 35 160	Glass wool	Yes

5. Cloisonement - Doublage - Plafonds suspendus - Menuiseries intérieures	**5. Partitioning, lining, suspended ceiling, interior carpentry**	
5.1 Cloisons et portes intérieures	**5.1 Portioning and Interior doors**	
Par 45	Glass wool	Yes
Bloc-porte bois de communication (avec huisserie métallique)	Wood door	Yes
Plaque de platre Placoplatre® BA13	Plasterboard Placopatre	Yes
5.2 Doublages mur, matériaux de protection, isolants et membranes	**5.2 Wall lining, protection, insulation and membranes**	
Par 45	Glass wool	Yes
Isoconfort 35 60	Glass wool	Yes
Plaque de platre Placoplatre® BA13	Plasterboard Placopatre	Yes
Placodur® BA18 18 mm	Plasterboard Placodur	Yes
5.3 Plafonds suspendus	**5.3 Suspended ceiling**	
Plafond suspendu en plaque de plâtre [ép.12,5mm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Suspended ceiling	Yes
6. Façades et menuiseries extérieures	**6. Façades and exterior carpentry**	
6.1 Revetement, isolation et doublage exterieur	**6.1 Cladding, insulation and exterior lining**	
BARDAGE EN LAMES PEINTES DE BOIS RESINEUX FABRIQUE EN FRANCE	Wood cladding, softwood	Yes
BARDAGE EN LAMES BRUTES ISSU DE BOIS FRANCAIS FEUILLU NATURELLEMENT DURABLE FABRIQUE EN FRANCE	Wood cladding, hardwood	Yes
Bardage en acier - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Steel cladding	Yes
6.2 Portes, fenetres, fermetures, protections solaires	**6.2 Doors, windows, sun protections**	

VOLET ROULANT ALUMINIUM MANUEL	Roller shutter	Yes
Fenêtres et portes fenêtres en PVC teinté dans la masse ou plaxé, à double vitrage	Windows in PVC, double glazing	Yes
7. Revetements des sols, murs et plafonds - Chape-Peintures - Produits de décoration	**7. Coverings**	
7.1 Revetement des sols	**7.1 Flooring**	
Plinthe en bois massif [haut. 7cm et ép. 1,4cm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Wood plinth	No
Plinthe en PVC [haut. 7cm et ép. 1,1cm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	PVC plinth	No
Chapes / chapes flottantes en béton et mortier à base de ciment - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Floating screed, in concrete	Yes
Isolants thermiques et acoustiques sous chape en polyuréthane [R=5m².K/W] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Polyurethane insulation	Yes
Revêtement de sol PVC en dalles et lames décoratives (LVT)	PVC flooring in slabs and decorative strips	Yes
Carrelage grès cérame émaillé EMILCERAMICA	Ceramic tiling	Yes
7.2 Revetement des murs et plafonds	**7.2 Wall covering**	
Peinture AQUARYL MAT + - UNIKALO	Painting Aquaryl	Yes
Revêtement pour murs et plafonds en faience [ép. 10mm] avec mortier colle et joint - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Faience wall	No
Membrane d'étanchéité pour carrelage (avec colle) [ép. 0,7mm] - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Waterproofing membrane, for tiling	No
7.3 Elements de décoration	**7.3 Decoration**	
Lasures en phase aqueuse	Stain wood	Yes
Peintures pour boiserie en phase aqueuse - DONNEE ENVIRONNEMENTALE PAR DEFAUT	Wood paints	Yes
8. CVC	**8. HVAC**	

Lot forfaitaire - Maison individuelle - Lot 8 - CVC (Chauffage - Ventilation - Refroidissement - Eau Chaude Sanitaire) - DONNEE ENVIRONNEMENTALE CONVENTIONNELLE	HVAC system (heat pump, electric convector and ventilation system)	Yes
9. Installations sanitaires	**9. Sanitary facilities**	
Lot forfaitaire - Maison individuelle - Lot 9 - Installations sanitaires - DONNEE ENVIRONNEMENTALE CONVENTIONNELLE	Bathtub, tap, shower, WC	Yes
10. Réseaux d'énergie	**10. Energy networks**	
Lot forfaitaire – Maison individuelle – Lot 10 – Réseaux d'énergie (courant fort) - DONNEE ENVIRONNEMENTALE CONVENTIONNELLE	Electrical cabinet and networks	Yes
11. Réseaux de communication	**11. Communication systems**	
Lot forfaitaire – Maison individuelle – Lot 11 – Réseaux de communication (courant faible) - DONNEE ENVIRONNEMENTALE CONVENTIONNELLE	-	No

Table III-3: End of life scenarios for steel products

Construction product	Baseline	Worst case	Best case
Wood door, with metal frame	100% landfill	= Baseline	100% Recycling
Steel cladding	4% landfill 81% recycling 15% reutilization	100% Landfill	100% Recycling
Metallic sheet	20% landfill 80% recycling	100% Landfill	100% Recycling
Precast concrete slab	33% landfill 67% recycling	100% Landfill	100% Recycling
Exterior wall in reinforced concrete	25% landfill 75% recycling	100% Landfill	100% Recycling
Floating screed	100% landfill	= Baseline	100% Recycling

Table III-4: End of life scenarios for concrete products

Product	Baseline	Worst case	Best case
Manhole	100% landfill	= Baseline	100% Recycling
Concrete slab for road network	100% landfill	= Baseline	100% Recycling
Concrete paving block	26% landfill 74% recycling	100% Landfill	100% Recycling
Bedding concrete	100% landfill	= Baseline	100% Recycling
Concrete shuttering block	30% landfill 70% recycling	100% Landfill	100% Recycling
Precast concrete slab	33% landfill 67% recycling	100% Landfill	100% Recycling
Exterior wall in concrete	25% landfill 75% recycling	100% Landfill	100% Recycling
Floating screed	100% landfill	= Baseline	100% Recycling

Table IV-5: End of life scenarios for wood products

Product	Baseline	Worst case	Best case 1	Best case 2
Wood fence	100% landfill	= Baseline	100% Recycling	100% incineration
Wooden floor	17% landfill 57% recycling 26% incineration	100% Landfill	100% Recycling	100% incineration
Wall timber frame	18% landfill 66% recycling 16% incineration	100% Landfill	100% Recycling	100% incineration
Resinous frame	17% landfill 57% recycling 26% incineration	100% Landfill	100% Recycling	100% incineration
Wood cladding	26% landfill 57% recycling 17% incineration	100% Landfill	100% Recycling	100% incineration

Annex IV

Supplementary information for Chapter 5

Table IV-1: Relative impacts GMTC and relative time of temperature peak of the building's contributors

	time_abs (year)	impact_abs (K)	time_relative	impact_relative
H&MEWS	60	1.35E-11	0.07	-0.94
F&I	60	3.26E-11	0.07	-0.86
S&M	55	2.74E-11	-0.02	-0.89
RTFF	60	-6.58E-14	0.07	-1.00
P&IC	58	2.99E-11	0.04	-0.88
F&EC	57	7.06E-12	0.02	-0.97
Coverings	53	2.05E-11	-0.05	-0.91
HVAC	48	4.41E-11	-0.14	-0.82
SF	54	7.63E-12	-0.04	-0.97
EN	56	1.37E-11	0.00	-0.94
Energy consumption	56	4.98E-11	0.00	-0.79
Building total	**56**	**2.39547E-10**		

Table IV-2: Comparison of conventional LCA ranking between from the Observatory project and our case study's building

	Conventional LCA ranking of the Observatory project	**Conventional LCA ranking of our case study's building**
1	S&M	HVAC
2	HVAC	S&M
3	H&MEWS	F&I
4	F&EC	H&MEWS
5	EN	Coverings
6	Coverings	RTFF
7	F&I	P&IC
8	F&IC	F&EC
9	RTFF	EN
10	SF	SF

Table IV-3: Relative impacts (CRF at 100th year) of prospective scenarios (worst and best) with respect to the baseline scenario – calculated by conventional and dynamic LCA

DYNAMIC ASPECT		Contributor	WORST CASE			BEST CASE		
				Relative CRF by conventional LCA	Relateive CRF by DLCA	Scenario name	Relative CRF by conventional LCA	Relateive CRF by DLCA
Technological advancements	Innovation on material	Insulation	Insulation, worst case	3.79	4.69	Insulation, best case, bio based	0.43	-4.22
						Insulation, best case, recycled material	-0.43	-0.42
	End of life progress		-	-	-	Insulation, recycling	-0.15	-0.40
	Innovation on material	Windows	-	-	-	Windows, recycled content in glazing	-0.01	-0.25
	End of life progress		Windows, landfill	0.01	0.02	Windows, recycling	-0.14	-0.24
	End of life progress	Heat Pump and Electric Convector	HVAC, landfill	0.04	0.01	HVAC, recycling	-0.02	-0.10
		Concrete products	Concrete products, landfill	0.02	0.05	Concrete products, recycling	-0.03	-0.05
		Wood products	Wood products, incineration	-0.17	-0.16	Wood products, recycling	-0.17	0.10
			Wood products, landfill	0.26	-0.04			
		Steel products	Steel products, landfill	0.59	1.22	Steel products, recycling	0.00	-0.03
Material degradation	Thermal properties of insulation material	Electricity consumption	Energy consumption, insulation degradation, linear	0.02	-0.04	Energy consumption, insulation degradation, nonlinear	0.10	0.08
	Thermal properties of airtighness material		Energy consumption, airtightness	0.08	0.01	-	-	-
Equipment degradation (heat pump and electric convector)	Energy efficiency loss		Energy consumption, equipement degradation, worst case	0.07	0.00	Energy consumption, Efficiency loss, best case	0.02	-0.04
Electricity Mix	Change of electricity mix		Energy consumption, ADEME worst case	-0.12	-0.24	Energy consumption, ADEME best case	-0.14	-0.26
Typology of occupants	Change of inhabitants number		Energy consumption, inhabitants change	0.03	0.03	-	-	-
Technological advancements	Energy consumption for producing construction products	Primary energy to product construction products	Energy efficiency, best case	-	-	Energy efficiency, best case	-0.04	-0.17

Table IV-4: Relative impacts GMTC and relative time of prospective scenarios (worst and best) with respect to the baseline scenario – calculated by dynamic LCA

Dynamic aspect		Contributor	WORST CASE			BEST CASE		
			Scenario name	Relative time	Relative GMTC	Scenario name	Relative time	Relative GMTC
Technological advancements	Innovation on material	Insulation	Insulation, worst case	-0.31	8.86	Insulation, best case, bio based	-0.78	-0.78
						Insulation, best case, recycled material	-0.29	-0.41
	End of life progress		-	-	-	Insulation, recycling	0.16	-0.56
	Innovation on material	Windows	-	-	-	Windows, recycled content in glazing	-0.57	-0.49
	End of life progress		Windows, landfill	0.00	0.03	Windows, recycling	-0.57	-0.48
	End of life progress	Heat Pump and Electric Convector	HVAC, landfill	0.00	0.06	HVAC, recycling	0.00	-0.04
		Concrete products	Concrete products, landfill	-0.03	0.16	Concrete products, recycling	0.00	-0.08
		Wood products	Wood products, incineration	0.19	-0.60	Wood products, recycling	0.00	0.70
		Steel products	Steel products, landfill	0.00	2.50	Steel products, recycling	0.00	-0.07
Material degradation	Thermal properties of insulation material	Electricity consumption	Energy consumption, insulation degradation, linear	0.00	0.08	Energy consumption, insulation degradation, nonlinear	0.00	0.11
	Thermal properties of airtighness material		Energy consumption, airtightness	0.00	0.08	-	-	-
Equipment degradation (heat pump and electric convector)	Energy efficiency loss		Energy consumption, equipement degradation, worst case	0.00	0.07	Energy consumption, equipement degradation, best case	0.00	0.02
Electricity Mix	Change of electricity mix		Energy consumption, ADEME worst case	0.09	-0.19	Energy consumption, ADEME best case	0.07	-0.22
Typology of occupants	Change of inhabitants number		Energy consumption, inhabitants change	0.00	0.04	-	-	-
Technological advancements	Energy consumption for producing construction products	Primary energy consumpion for construction products	-	-	-	Energy efficiency, best case	0.00	-0.03

Table IV-5: Emission timing analysis of 10 families of construction products