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2 **An operational methodology for applying dynamic Life Cycle Assessment to buildings**

3

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19

20 Abstract:

21 While the Life Cycle Assessment (LCA) method is a powerful tool for environmental performance
22 evaluation, the current LCA methodology faces some limitations in evaluating environmental
23 performances of systems with a long time scales, such as buildings. Building systems have particularly
24 long lifetimes as compared to other products or services. They are composed of elements that evolve
25 over time and are characterized by time-dependent parameters. A literature review was performed in
26 the aim of identifying the time-dependent characteristics of a building system at different levels:
27 building technology level (e.g. technical performance degradations and technological innovations),
28 end-user level (e.g. occupant behaviour) and external system level (e.g. infrastructures, energy mix,
29 regulations). A new LCA framework including the time dimension, applied to a building system, is
30 proposed. It involves operational and reproducible tools (computational software and databases) to
31 perform effective temporal evaluations and incorporates dynamic Life Cycle Inventory (LCI,
32 including the temporal evolution of a building system and of the related environment interventions, i.e.
33 emissions and resource consumption) and dynamic Life Cycle Impact Assessment (LCIA, climate
34 change and toxicity). To integrate the specificities of buildings in dynamic LCI modelling, different
35 existing assets (at national and international level) in the field of LCA are analysed. This work
36 proposes an original methodology for performing a dynamic LCA of buildings using new tools still
37 under development.

38

39 Keywords:

40 Building, dynamic Life Cycle Inventory, dynamic Life Cycle Impact Assessment

41

42 Highlights :

- 43
- 44 • We propose a methodology for realising time dependent LCA of buildings
 - 45 • Advanced tools for dynamic LCI and dynamic LCIA are combined together
 - 46 • Temporal characteristics were identified in all stages of building's lifetime
 - 47 • Temporal parameters and specific data are collected in a dedicated database

47

48 1. Introduction

49 Life Cycle Assessment (LCA) has become an indispensable method for quantifying the environmental
50 performance of products or services and is widely used in many sectors of activity. Environmental
51 issues of buildings concerning both energy and embodied materials have increasingly been
52 acknowledged by several scholars, who have illustrated their methodological developments for
53 environmental assessment of buildings through case studies [1–3]. Different types of building
54 structures, scenarios of replacement and refurbishment phases, construction products, and end-user
55 energy consumption have been compared in terms of their environmental performance. Moreover,
56 some studies have focused on energy use throughout the building lifetime, investigating how to
57 estimate orders of magnitude of energy uses from the construction to demolition of the building [4,5].
58 The considerable amount of waste resulting from the construction activity and the dismantling of
59 buildings has led us to consider demolition waste recycling. While building-LCA studies have seen
60 methodological improvements integrating more and more complex elements of the building system,
61 the evolution of that system over its life cycle has remained beyond the scope of studies, as buildings
62 have particularly long lifetimes compared to other products or services. Building systems are
63 composed of elements that evolve in time and are characterized by time-dependent parameters. At the
64 technological level related to the building sector, the degradation of technical performances of
65 buildings may be one of the key dynamic parameters. On the other hand, energy consumption varies
66 with time and its variation is determined by technological parameters, occupant behaviour, energy
67 equipment characteristics and climate conditions. Another aspect influencing energy consumption by a
68 building system is the economic and environmental context. The evolution of policy rules, e.g.
69 national energy strategies and environmental regulations, may encourage the construction sector to
70 reduce material and energy use and can stimulate a reduction of related environmental impacts e.g.
71 near zero energy and low carbon footprint buildings: the “E+C- approach”, a large-scale experiment
72 aiming to prepare a new environmental building regulation in France [6]. The European project
73 “Levels” is also based on the concept of applying a life-cycle approach to building design [7,8].
74 Therefore, decisions for construction materials, maintenance, replacements, and refurbishment,
75 together with scenarios of the end of life, should be placed in the context of national and European
76 regulations that change over time depending on the energy, environmental and economic background.
77 The electricity production mix and, more generally, the energy resources used vary over time with
78 regard to the availability of energy resources, the economic situation of a country, climate and
79 agriculture for renewable energy development, etc. Some of these dynamic parameters considerably
80 impact LCA results for buildings.

81 Many environmental standards currently exist in the field, at national levels as well as in Europe. For
82 example, the European standard EN 15978 on the assessment of the environmental performance of
83 buildings is applicable to new and existing buildings, and refurbishment projects [9]. These standards

84 give the rules for quantitatively evaluating the environmental performance of buildings based on the
85 life cycle approach. Different life cycle-based tools complying with these rules or environmental
86 regulations have been developed to help design sustainable buildings with respect to country-specific
87 contexts, e.g. ELODIE in France [10]. The specificities of some existing building-LCA tools will be
88 mentioned in the following sections. Even though efforts are being made on the development of LCA
89 tools along with efforts to regularly upload environmental data, none of these tools allow the temporal
90 dimension to be considered, either at the level of material and energy balance, or at the level of
91 environmental impact calculations. Actually, there are no tools (methods, norms, or databases)
92 enabling temporal characteristics to be taken into account that are explicit and specific to buildings.
93 Nevertheless, prospective evaluations can be performed by using specific energy and material balances
94 averaged over given time periods.

95 In this context, the need for a more realistic evaluation of the environmental performances over long
96 time frames leads us to consider a dynamic LCA approach adapted and completed for application to
97 the building sector. Thus, the general goal of this work is to propose a methodology for considering
98 time in LCA of buildings. In order to reach our goal, the present paper (i) aims to identify the main
99 temporal aspects of a building system (section 2), (ii) analyses the literature related to the dynamic
100 LCA assessment in the field of buildings, and (iii) proposes a framework for temporal LCA applied to
101 buildings. Key dynamic parameters of the building system, the method of dynamic inventory data,
102 calculation tools, expected results and also the main limitations of the proposed general framework are
103 presented.

104

105 **2. Time-dependent factors and parameters of a building system**

106

107 Before analysing the temporal aspect in LCA applied to buildings, this section will present the
108 temporal variation of building systems encountered from a variety of aspects.

109 Energy consumption varies from hour to hour, day to day, week to week, season to season, and year to
110 year, depending on various factors. The typology of inhabitants and their behaviour are variable
111 depending on the economy, culture, and climate, and play an important role in determining the energy
112 consumption level and its temporal behaviour. From a literature review, de Meester et al. [11] selected
113 the three parameters having most influence on the heating loads in a single-family house: 1) type of
114 occupancy (e.g. family size, age), 2) management of thermal comfort (e.g. temperature set point,
115 functioning time of energy systems) and 3) area heated. They created 7 levels of thermal performance
116 for the house (from zero insulation to standard level insulation for a passive house). Each scenario
117 uses different insulation materials in the wall, floors, and roof. If the insulation level is low, the heat

118 load management (temperature specification and heating time) becomes important to reduce energy
119 consumption. On the other hand, when the house is well insulated, the type of occupancy greatly
120 impacts the energy consumption level. Four scenarios of occupancy over 100 years, combining the
121 above three parameters, were evaluated in terms of heating loads, and the maximal difference between
122 scenarios reached 26%. As evoked in their discussion, in a long time scale analysis, the house should
123 be adapted to the evolution of the family, including possible improvements in thermal insulation.

124 Technical performances related to construction products and energy equipment degrade over the long
125 lifetime of buildings. Insulation materials deteriorate over time due to climate conditions (e.g.
126 humidity) and the occupant needs to replace such building materials in order to maintain the thermal
127 comfort. Studies exist on how the degradation of building components (especially insulation materials)
128 occurs over time, affecting the energy consumption [12–14]. One of these research works examined
129 the durability of insulation materials in terms of their thermal-hygrometric and mechanical
130 performances, showing a 12% increase in thermal conductivity over 25 years. The effects of such
131 degradations on the energy performance of buildings was observed and simulated over time for
132 different envelope structures e.g. exterior walls, floors, and roof. Marceau et al. [15] showed that bio-
133 based insulation materials, such as wood wool are particularly sensitive to climate conditions, and
134 their thermal performance can deteriorate due to the variation of water content in the products.
135 Degradations of technical performance will lead to changes in energy consumption. Besides, the
136 interaction with external factors like gases from atmosphere may lead to some carbon dioxide
137 absorption in case of lime-containing materials (concrete, hempcrete, ...) [16,17]

138 The real durability of construction products can be significantly different from the theoretical and
139 declared one [18]. ISO 15686-8 defines a methodology and factors to determine the service lifespan of
140 construction products and building equipment. According to the literature review, many building-LCA
141 studies refer to 50 to 100 years as a lifetime of buildings. The service life of 30 years is typically used
142 for principal components of a building (e.g. floors, façades, and roof) [8] and products should be
143 replaced or refurbished at their end of life using new technologies that have emerged.

144 Although the technical performances of building components may diminish during the building's long
145 lifetime, this very longevity of the building implies that it will be able to benefit from technological
146 innovations occurring after its original construction. The relevance of taking this prospective aspect
147 into account in LCA for long time scale studies has been discussed by Frischknecht et al. [19].
148 Prospective factors should be considered for different scales and depending on the scope of the study.
149 Replacement, refurbishment and also the treatment of construction waste products occurring several
150 decades after the first construction may use new technologies that are more efficient in terms of energy
151 consumption or environmental emissions. Thus, industrial and technological improvements should
152 lead to long time scale scenarios with high environmental quality of the buildings.

153 Reducing energy consumption during the building component production and during its service
 154 lifetime is a continuing goal. Lowering the environmental load of the energy used is another
 155 improvement criterion. Heat production can use thermal resources like fossil fuels, biomass, and
 156 thermo-solar systems. A large panel of electricity production technologies exist, based on fossil or
 157 renewable resources. French electricity production depends strongly on nuclear power and is
 158 characterized by a low carbon footprint, with an annual average of 105 gCO₂ eq/kWh, compared to the
 159 power production technologies of other European countries, which are mostly based on fossil fuels.
 160 For example, the average carbon intensity of electricity consumed in Europe was 447 g CO₂-eq/kWh
 161 in 2013 [20].

162 To meet the target concerning the reduction of GHG emissions, the European Commission has
 163 proposed a framework for energy pathways towards 2050. Following this strategy, 75% of the
 164 European electricity consumption would be covered by renewable sources, with a shift in the
 165 electricity production mix and improvements in energy system efficiency [21]. Decarbonisation is also
 166 encouraged for heating and cooling systems to ensure that the goal of limiting climate change is
 167 achieved [22]. According to this study, increasing the share of district heating with respect to the total
 168 energy demand, and also accounting for the development of other heating systems (waste incineration,
 169 geothermal, solar thermal and industrial excess heat), would reduce carbon emissions at European
 170 level by 17 to 30% by 2050 with respect to the same heat demand level as in 2010. Also included in
 171 the scenario are other temporal changes in heat production systems: decreasing nuclear production,
 172 renewing power plants and existing combined fossil-fuelled heat and power (CHP) plants, and
 173 developing renewable heat production. In France, the national energy strategy aims to increase the
 174 proportion of renewable energy resources to 40% by about 2030 and reducing the nuclear production
 175 fraction from 75% to 50% by 2025 [23]. In terms of French district heating systems, the objective for
 176 2030 is to cover 32% of district heat consumption by renewable energy resources. The quantity of
 177 renewable heat and cooling delivered in 2012 will be multiplied by five in 2030, which will represent
 178 3.2 Mtoe (equal to 41.9 TWh).

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

181

182 *Table 1: 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	[12–15,24]	Technical performances (thermal, acoustic, mechanical resistances of materials),	Year to decade ~

		Service lifetime of construction products and materials, Material quantities	
HVAC (Heating, Ventilation, and Air-Conditioning) system	[25,26]	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)	[27,28]	Electricity production by photovoltaic system	Hour, day, month, season to several decades
Occupant behaviour	[11]	Thermal management Typology of family Insulation material choices	Year to decade ~
Energy production (electricity and district heating and cooling)	[27,29,30]	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	[24]	Quantity of carbon dioxide absorbed by and emitted from wood	Several decades to century
Carbon sequestration in other materials	[16,17]	Quantity of carbon dioxide absorbed by e.g. lime-containing products	Years, several decades
Retrofitting scenario	[31]	Technical performances of materials	Decade ~
Demolition scenario	[24]	Energy recovery and recycling technologies	Decade ~

183

184

185

186 3. Considering temporal aspects in LCA applied to buildings

187 3.1. Time-related aspects in conventional LCA

188 LCA is the common method for evaluating products, services, and activities in terms of their potential
189 environmental impacts throughout their life cycle, supported by ISO 14040 – 14044 standards [32,33].
190 According to the standards, LCA methodology is divided into four steps. i) Goal and scope definition.
191 ii) Life cycle inventory compilation calculating material and energy balances at the level of the
192 processes and of the environmental interventions (substances emitted into the environment and natural
193 resources consumed), throughout the system's lifespan. While the LCI of background processes is
194 generic and can be obtained from databases, the foreground process inventory is case-specific and
195 must be obtained by data collection or specific modelling for the process/product under study. iii) Life
196 cycle impact assessment based on methods for evaluating environmental impacts. iv) Interpretation of
197 LCA results, as a consequence of time dimension included mainly in the first three steps of the
198 methodology.

199 The analysis time span is the period used for each system studied, chosen in coherence with the
200 lifetime of this system. It is specified in the first step of LCA, i.e. the definition of the goal and scope,

201 and represents the period for which the established inventory is considered as reliable and the LCA
202 results are considered valid (e.g. 50 years, the lifespan of a building). In the same manner, the time
203 boundaries of a study situate the period of interest in time (e.g. a past or a future new system).

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

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

218 Various LCIA methods exist for calculating environmental impacts. The basic principle of all
219 conventional methods is to provide a characterization factor (CF) for a given combination of
220 substance/environmental compartment/effect (or impact). Then the substance amount (i.e. LCI) is
221 multiplied by its CF to obtain the impact result. This is the basic principle of LCA. In such an
222 approach, assumptions and simplifications were operated at the level of CF calculation, notably by
223 considering the environmental mechanisms in steady state (static) conditions, or considering a fixed
224 time horizon when an integral over time is required to calculate CF for some impact indicators (e.g.
225 GWP – global warming potential). Conventional characterization factors are thus dependent on
226 arbitrarily fixed time horizons (e.g. 20, 50, 100 years), which constitutes a strong limitation of the
227 current LCIA methods. It is completely legitimate to raise questions like, “Does today’s 1 kg of CO₂
228 emission have the same environmental impact as 1 kg emitted after 50 years?” Or, “Between 10 kg of
229 CO₂ emission in a year and 1 kg of CO₂ emissions per year during 10 years, which case has the most
230 impact at a precise date?” It is not possible to answer such questions within conventional LCA and a
231 new approach with fully dynamic modelling of environmental mechanisms is needed.

232 The relevance of taking account of the temporal dimension in the LCA, at both LCI and LCIA levels,
233 has been discussed in recent studies [34–36]. In the following, we analyse how the temporal
234 dimension is considered in previous studies dedicated to LCA of buildings.

235

236 3.2. Tools for LCA of buildings and their limitations

237 LCA is usually performed with dedicated software (e.g. SimaPro, Umberto, GaBi) and databases,
238 ecoinvent being the most general and widely used in the European area. As mentioned in the
239 introduction section, there are many LCA tools, software, and databases adapted to the construction
240 sector; several tools that were available for this work and were included in the new methodology are
241 presented here. ELODIE, a French LCA tool specific to buildings, is supported by INIES
242 (<http://www.base-inies.fr/iniesV4/dist/consultation.html>), a public database of environmental and
243 health data for construction products and building equipment. It includes Environmental and Health
244 Product Declaration (EHPD: FDES in French) conformity and PEP ecopassport®. The data recorded
245 in the FDES are values for environmental impact indicators declared in a voluntary way by the
246 industrials, especially concerning newly constructed buildings. FDES do not contain inventory data.
247 Data sets from INIES could provide more realistic and precise information for construction products
248 than other generic LCI datasets such as ecoinvent. The future French energy and environmental
249 regulations will be supported by the LCA method with its public inventory dataset for the construction
250 sector. FDES data for construction products are used by ELODIE software for calculating
251 environmental impacts of buildings.

252 Energy consumption during the service life can be calculated using models and software developed for
253 thermal performances of buildings.

254 COMETH, a calculation engine for the simulation of a whole building's thermal performance, could
255 be used to compute energy consumptions related to heating, cooling, domestic hot water, lighting and
256 ventilation at an hourly time step. The tool is compliant with the French thermal regulations. This
257 engine is easily configurable and allows to set the simulation boundary conditions, such as weather or
258 occupant behaviour, and the building description, such as geometry, level of thermal resistance of its
259 envelope and energy efficiency of equipment. The output of COMETH can be then used as an input in
260 ELODIE - LCA software. Another French LCA tool for buildings, named EQUER, can be linked to a
261 dynamic thermal simulation tool named COMFIE. This software allows time-varying energy
262 production mixes and energy consumptions to be taken into account when assessing environmental
263 impacts of building energy use at each time step, with historical weather data. As mentioned by
264 Lasvaux [10] summarizing principal building-LCA software and its databases, many other examples
265 of similar LCA calculation tools for buildings exist in different countries, e.g. One Click LCA
266 (German), ATHENA (Canada), IMPACT (United Kingdom), which are based on different guidelines
267 and contextual hypotheses (methodological choices, boundaries of an evaluated system, method of
268 impact calculation, etc.). For example, LEGEP is a tool for LCA of buildings developed in Germany
269 and it has an inventory dataset of more than 1000 construction materials complying with the European
270 standard EN15804 [37] defining the method of environmental assessment of construction products.

271 None of these tools, however, considers any time-varying characteristics of construction products and
272 equipment in the LCA study, nor can they differentiate the environmental interventions (emissions,
273 resources) over time. Moreover, these existing tools do not allow for dynamic impact evaluations e.g.
274 evolution of radiative forcing with time for climate change impact evaluation.

275 In addition to specifically dedicated tools for buildings, databases exist in the field of energy
276 production at national and European level. The European Commission has initiated the project “New
277 Energy Externalities Development for Sustainability (NEEDS)”, which gathers together international
278 industrial life cycle inventories on future electricity supply systems. Several scenarios are proposed for
279 the European energy mix by 2025 and 2050, which could be considered in a temporal perspective in
280 order to assess the influence of the grid mix evolution on LCA results.

281

282 3.3. Different ways of considering time in LCA of buildings

283 Scheuer et al. [38] mentioned that future LCA studies should attach more and more importance to
284 accounting for i) change in demand for materials and energy, ii) technical performances of energy
285 services and equipment, and iii) material burdens due to changes in the foreground system e.g. choices
286 of material, service lifetime of building components, as well as in the background system, e.g.
287 production efficiencies of building materials. While authors have argued their proposals to integrate
288 these dynamics in LCA, they did not have access to operational calculation tools to implement them in
289 an appropriate LCA framework.

290 Frijia et al. [26] investigated the contribution of manufacturing and construction phases to the life
291 cycle energy use. They proposed different functional units for a residential building, including all
292 domestic functionalities or only heating and cooling systems, to calculate the operational energy use.
293 They also assumed, in their case study, annual improvements in the energy efficiency of heat pumps
294 and air conditioning systems towards 2052, based on public data from the U.S. Department of Energy
295 and periodic replacement of HVAC (Heating, Ventilation, and Air-Conditioning) systems by advanced
296 technologies. Their LCA case study of residential houses revealed that, using an adapted functional
297 unit, which only included heating and cooling systems with a consideration of technological
298 improvement, the share of embodied energy use could be far higher than in previous studies, which
299 were based on the conventional functional unit.

300 Collinge et al. [29] proposed a dynamic LCA framework integrating temporal variability of industrial
301 processes for energy production and the influence of time on climate change impact calculations. The
302 development of their dynamic LCA method was based on the conventional matrix-based calculation of
303 LCA [39] and consisted of calculating the inventory and impacts by time periods, i.e. a scenario
304 approach. The functional units and reference flows were considered as parameters that could vary with

305 time from one period to another. They exploited existing public data on dynamic energy productions
306 (time variations of the grid electricity mix), and consumptions and related environmental interventions
307 to obtain a distinct LCI per time period. Temporal variations of processes in the background system
308 (energy production industry) were considered, as were different shares of energy resources over time
309 (the supply chains). The building use phase was studied with particular attention due to the important
310 environmental impact generated by energy consumption in this phase. Time-adjusted global warming
311 potentials were used to calculate climate change impact following Kendall's method of time horizon
312 correction [40], and using seasonal characterization factors for photochemical ozone formation [41].
313 This work brought out the importance of considering time in LCA of buildings. However, access to
314 the specific building data (e.g. energy consumption, emissions) and the separate collection of
315 inventory data for many periods might be the main limitation of their work.

316 Fouquet et al. [24] performed a comparative study of the static versus dynamic LCA for three low-
317 energy buildings: 1) concrete cavity wall, 2) concrete double wall and 3) timber frame. This study also
318 addressed the relevance of accounting for a temporal profile of CO₂ balance through the uptake due to
319 the growth of trees until the release into the atmosphere at their end of life. The scope of the CO₂
320 balance should be well defined by considering forest management (i.e. timing of CO₂ uptake) and
321 waste management scenarios at the building end-of-life (i.e. landfilling or incineration of woods
322 leading to emissions of biogenic carbon dioxide), which would lead to significant differences in the
323 results calculated for climate change impact. Scenarios of grid mix were considered at time horizons
324 of 2025 and 2050 based on given prospective LCI data sets from the ecoinvent database and from the
325 publicly available database, NEEDS. They also paid particular attention to possible technological
326 innovation in the background system related to cement production using an improved production
327 technology. Time-dependent CFs were used for climate change impact calculations, following the
328 method proposed by Levasseur et al. [42]. With this specific case study, it was acknowledged that
329 dynamic LCA could alter the conventional interpretation of LCA results, thus providing a better
330 understanding of the environmental behaviour of building systems.

331 Electricity consumption and the method used for its production exhibits marked temporal variation in
332 both the short term, e.g. due to daily occupant behaviour or weather conditions, and the long term, e.g.
333 due to the increase in renewable energy technology in electricity mix production, and due to climate
334 change. Integrating renewable energy and auto-consumption systems in buildings, e.g. photovoltaic
335 system on the roof, requires more detailed analysis of LCI data over time [27]. The high temporality of
336 this energy aspect has always been considered in LCA studies. Peuportier and Herfray [43] developed
337 a dynamic and prospective LCA model to exploit historical data on public electricity (provided by
338 Electricity Transmission Network) differentiated in given time steps from an hour to a year. Energy
339 consumptions of testbed buildings were obtained at hourly or monthly time steps and then injected
340 into the LCA study based on EQUER software in order to evaluate global warming potential (GWP).

341 The impact was calculated by multiplying environmental emissions at each time step (from the French
342 electricity grid) by the corresponding characterization factor (for instance, $CF=1\text{kgCO}_2\text{-eq/kgCO}_2$ for
343 carbon dioxide). The dynamic electricity production mix model was based upon time-varying
344 productions for each fuel type and based on a given atmospheric temperature. Following this study,
345 Roux et al. [28] improved the approach by integrating a temporal variation of local energy production
346 by the on-roof photovoltaic system. The improved methodology was applied to testbed cases of three
347 low-energy buildings to evaluate their environmental performances and acknowledged the discrepancy
348 between static and dynamic LCA results. The time step of the LCI model concerning the energy
349 consumption and production was considered as a key element for the relevance of dynamic LCA
350 results and should be adapted to each case study with respect to local conditions (e.g. climate, energy
351 equipment, occupant behaviour). However, this study was limited to only one year for the energy use
352 phase of buildings. Nevertheless, these studies have the virtue to include commonly used simulation
353 tools in the field of energy efficiency of buildings in a temporal representation of the life cycle
354 inventory, moving forward with respect to other studies [44,45] in which the simulation results of
355 dynamic energy demand are used in LCA in an integrated form, as a single total energy value over the
356 building's lifecycle.

357 Recently, Su et al. [46] assessed the state of the art of dynamic LCA for buildings, mentioning that the
358 recent developments lack a temporal consideration of socio-economic parameters (technological
359 progress of building components, occupant behaviour). They also proposed the use of time-varying
360 weighting factors in the LCIA phase. These factors could be used to attribute different weights to
361 different impact categories in order to transform them into a single indicator e.g. monetizing LCA
362 results in order to compare systems based on a single end-point impact. However, the authors did not
363 identify the appropriate tools, i.e. models, software, databases or data providers, they expected to use
364 when implementing the proposed approach. Their development still remains only a theoretical concept
365 without a concrete application to a case study.

366

367 **4. Discussion and presentation of new approach**

368 4.1. General trends from the state of the art

369 While the LCA method is a powerful tool for environmental performance evaluation, the current
370 practice of LCA has not integrated a proper analysis of the environmental performance of systems
371 with a longer time scale, such as building systems. Several of the previous building-LCA studies
372 considered temporal characteristics but limited them rather to the LCI or LCIA steps. Another
373 common limitation of these previous studies is that several temporal aspects are considered only in the
374 foreground system or targeted on a few background processes (e.g. future technological improvement
375 of a particular process). The general temporal behaviour of the supply chains with their time-shifted

376 occurrence is not considered although, on a long lifetime scale, emissions occurring at different time
377 horizons would have very different impacts. Concerning the LCIA step, only a few environmental
378 flows of existing inventory data related to the case studies have been used, most of them only for
379 climate change impact. The existing proposed methodologies lack a general operational method and
380 calculation tools, i.e. software, coherent temporal databases, that could be applicable to any case study.

381

382 4.2. Identification of key dynamic aspects

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

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

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

403 *Energy production equipment.* The European and French energy and environmental regulations
404 envision an ever increasing percentage of renewable based energy production, and also the integration
405 of more local renewable energy systems, as discussed in section 2. The degradation of the production
406 capacity of existing energy production equipment over time would negatively affect the environmental
407 impacts over the whole life cycle of a building. On the other hand, progress at the level of energy
408 production technologies and equipment could reduce the environmental impacts of such systems and
409 consequently of the buildings. After reviewing some previous studies, we propose the integration of
410 technological changes in energy production equipment into the dynamic assessment.

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

416 *Biogenic carbon emission and carbon uptake.* The current LCIA methods (e.g. EN15978) do not
417 include biogenic carbon (e.g. carbon dioxide emissions from biomass in the GWP calculation) as a
418 factor of climate change. However, as mentioned by [24], for a building composed of significant
419 amounts of wood, it is relevant to take all flows of CO₂ from the tree growth phase (CO₂ uptake from
420 atmosphere) to the end of the life of the building (CO₂ emissions into the atmosphere). Carbon that is
421 sequestered in wood during tree growth would be released into the air through the combustion or
422 degradation of wood-based materials at the end of life stage. Carbon dioxide can also be absorbed
423 from the atmosphere by materials having a high content on basic substances, e.g. rich on lime. This
424 process is slow and takes place over decades. For these reasons, it is important for a time span large
425 enough for LCI to be included in the scope of the study in order to encompass all these processes,
426 from forestry management to end of life scenarios. A dynamic LCI approach will allow these different
427 processes to be placed on a time scale. Notably CO₂ uptake and emissions will be separated by long
428 periods of time (e.g. more than 100 years in case of wooden buildings) and no compensation will
429 operate between them (in conventional LCA, CO₂ emissions and uptake take place at the same time
430 and, being of opposite sign, they compensate each other when summed up in the inventory step). This
431 will have a significant influence on the results for climate change impact, in contrast with conventional
432 LCA.

433 *End of life technologies.* There are many kinds of technologies for waste treatment at the end of the
434 life of building components and the building itself, depending on the nature of waste (e.g. inert waste,
435 dangerous and non-dangerous waste) and the type of materials present in the waste (e.g. concrete,
436 wool, plastic, etc.) [47]. After long lifetimes of several decades to 100 years, end of life technologies
437 and related infrastructures (e.g. recycling processes, energy production mix) will probably have
438 evolved with respect to current technologies. The current practice of LCA can take into account
439 prospective improvements of technologies into the calculation of inventory data. However, ignoring
440 time lags of emissions between the construction and the end-of-life phases, as performed in
441 conventional LCA, would bias impact calculations, especially for climate change impact, by
442 compensations (as explained above for the case of biomass) or by the instantaneous and simultaneous
443 emission hypothesis.

444

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

1. Occupant behaviour scenario	2. Construction products	3. Energy equipment	4. Energy mix scenario	5. Carbon uptake/emission	6. End of life technologies
<ul style="list-style-type: none"> • Typology of family • Presence time of occupants • Thermal comfort level 	<ul style="list-style-type: none"> • Degradation of technical performances of building components • Replacement and refurbishment with new technology 	<ul style="list-style-type: none"> • Integration of renewable energy systems • Deterioration of production capacity of energy equipment 	<ul style="list-style-type: none"> • Modifications of energy mix (electricity and heat) in the long term, based on national strategies 	<ul style="list-style-type: none"> • Carbon uptake during the growth of trees • Carbon uptake by construction products • Biogenic carbon emission at the end of life 	<ul style="list-style-type: none"> • Improved recycling rate or energy recovery can be integrated

447

448

449 4.3. Principles of the dynamic LCA method

450 A dynamic LCA method was recently proposed, providing adapted calculation tools. Tiruta-Barna et
 451 al. [48] proposed a temporal model for LCI, which considers the complex supply chains and processes
 452 that compose the life cycle system, for both foreground and background processes. This calculation
 453 tool, named DyPLCA (available at <http://dypclca.pigne.org/>), delivers the dynamic inventory, i.e.
 454 environmental interventions by substance/process and aggregated by substance, distributed in time.
 455 The dynamic LCI model can be linked to a conventional LCA database (ecoinvent for instance), which
 456 facilitates its use by LCA practitioners. A temporal database is included in DyPLCA, containing the
 457 time-dependent parameters of processes and supply chains associated with the datasets existing in
 458 ecoinvent 3.2.

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

465 Whatever the mode of use, the results provided by DyPLCA as environmental interventions
 466 distributed in time are then used with adapted LCIA dynamic models. Currently, there are very few
 467 dynamic models for calculating impact indicators in function of time. In [49–51] a dynamic climate
 468 change model and a dynamic toxicity model are developed and applied with the dynamic LCI to
 469 several case studies. In these methods, data and phenomenological dynamic models were

470 implemented: (i) from IPCC [52] for climate change, and (ii) from the USEtox® 2 model [53,54] for
471 toxicity impact categories. The complete framework was successfully tested on case studies by [55]
472 and, from now on, it can also be used for building systems. These dynamic LCIA methods were
473 implemented with the DyPLCA tool.

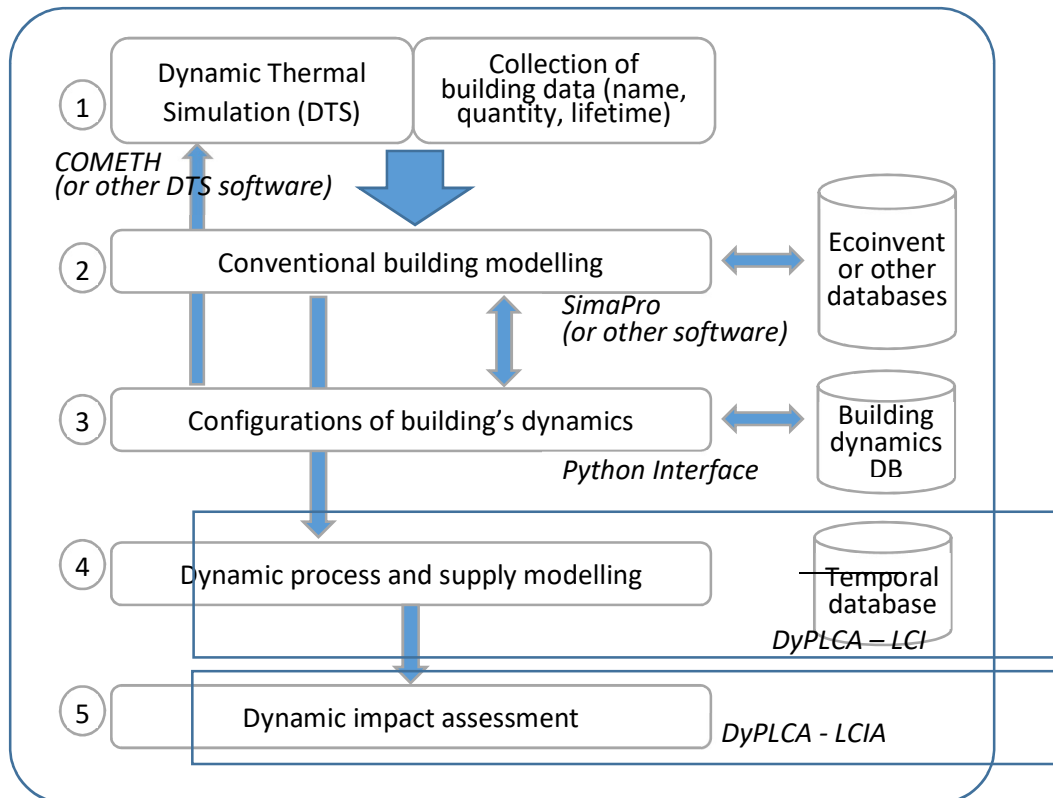
474 The proposed methodology for dynamic LCA of buildings relies on the dynamic LCA approach and
475 tools presented above.

476

477 4.4. Proposed methodology for dynamic LCA of buildings

478 In the building sector, temporal characteristics of systems can be summarized at three levels: building
479 technology level (e.g. technical performance degradations and technological innovations), end-user
480 level (e.g. occupant behaviour) and external system level (e.g. infrastructures, energy mix). These
481 characteristics are represented by temporal parameters of buildings explained in the previous section
482 and in Table 2, and should be integrated into fore- and background parts of the inventory. Many of the
483 time variable parameters considered in the present framework are related to technologies and materials
484 of building components, which contribute significantly to the total impact of a building system. On the
485 other hand, dynamic energy consumption and energy mix evolution with technological breakthroughs
486 related to renewable resources and energy management systems (energy storage, smart grids, etc.) are
487 also important contributors. This is because the impact from energy use during the building
488 operational phase depends greatly on the energy production technologies (the background system in
489 LCA). The proposed general framework for the dynamic LCA of buildings is shown in Figure 1: Main
490 steps of the proposed methodology for Dynamic LCA of buildings.

491



492

493 *Figure 1: Main steps of the proposed methodology for Dynamic LCA of buildings*

494

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

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

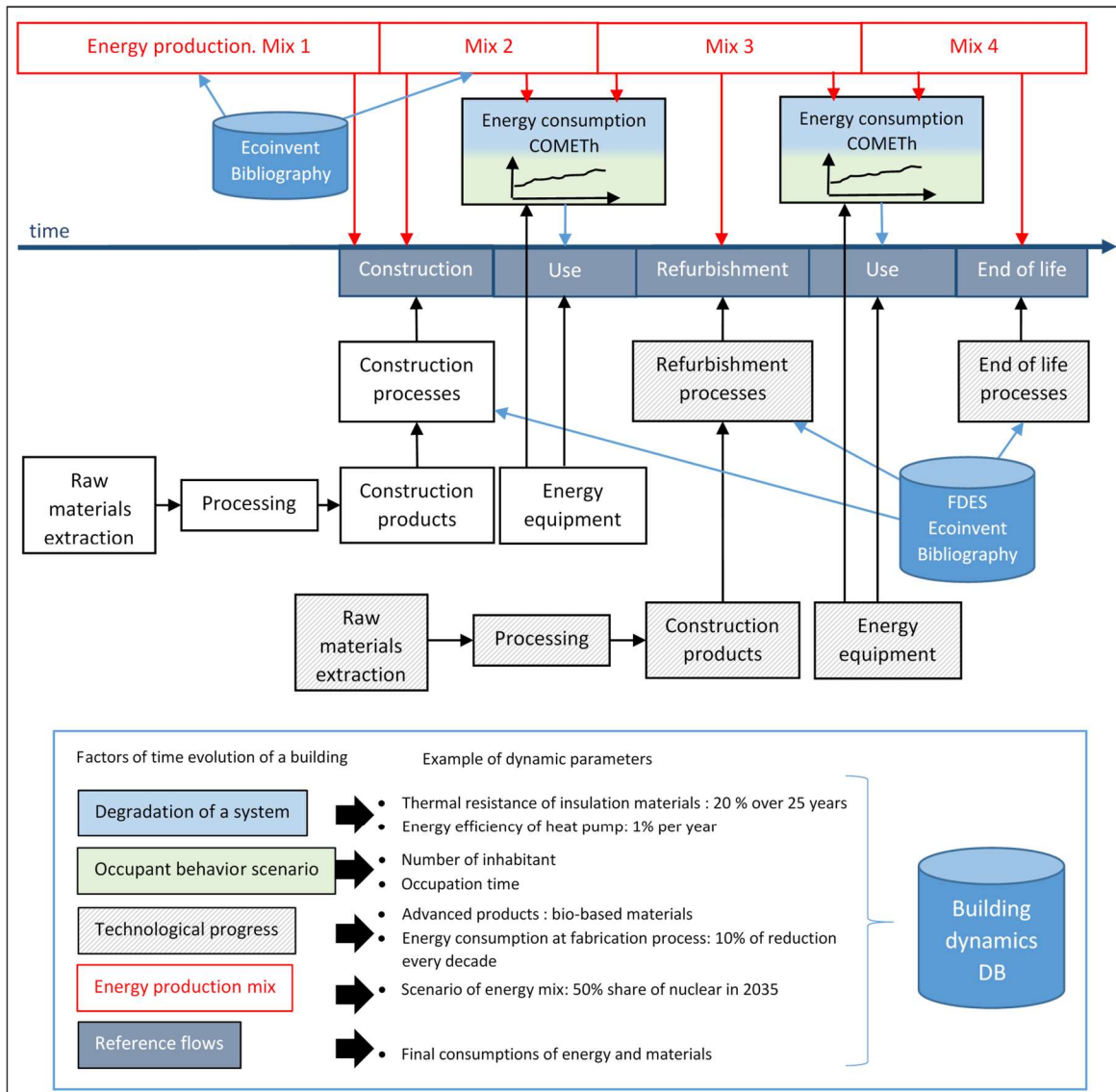
513 of elementary flows. Concerning the foreground part of the life cycle system, any data set (collected
514 on site, modelled, from specific databases) can be used, as is currently done in static conventional LCI
515 modelling.

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

537 *Step 4* (Dynamic model of the supply-chain): Technological and environmental matrix, created from
538 the model in SimaPro or other LCI calculation tool, is then used as input to the DyPLCA tool.
539 DyPLCA contains a database of temporal parameters associated with processes in ecoinvent 3.2,
540 useful for the LCI temporalization of the background processes and supply chains. The building, with
541 its three stages, i.e. construction, use and end of life, represents the foreground part of the life cycle
542 system. The temporal characteristics of the foreground (processes and supply chains) are defined by
543 the user; for example: construction takes 11 to 13 months [56] before the building operation phase
544 starts, considering that there is no time lag between the end of construction and the beginning of the
545 building operation phase; renovation of floors occurs after 50 years and takes several months, etc. The
546 output from DyPLCA is environmental intervention flows (e.g. kg/day) according to time (in csv
547 format).

548 *Step 5* (Dynamic model of the impact assessment): Using the temporal discrete LCI (output from
549 DyPLCA), temporal indicators for environmental impacts will be calculated. As mentioned before,
550 dynamic climate change, human toxicity, and ecotoxicity are the impact categories for which dynamic
551 models have been implemented. In addition, the inventory can be also used for classical impact
552 assessment by calculating the partial or total integral of the flows over time.

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



562

563 *Figure 2: Time dimension of a building system and methodology application*

564

565 The different tools specific for the building are also placed on the scheme. Inventory data for building
 566 related processes comes from databases like FDES, ecoinvent or others, and from literature. Inventory
 567 data for very background processes (e.g. electricity production) are rather generic and comes from
 568 ecoinvent database. These static data are transformed in time-dependent data thanks to the building
 569 dynamics DB and then of the DyPLCA tool. Technological and elementary flows of foreground
 570 processes are calculated at the process level with the consideration of dynamic parameters, leading to
 571 variable reference flow per process (e.g. decrease of the heat demand in use phase due to climate
 572 change, occupancy, etc.). The factors and parameters affecting the time evolution of building (i.e. the
 573 reference flows of different processes in the building's life cycle) are collected in the building
 574 dynamics DB. These parameters are used with appropriate models for calculation of material and
 575 energy consumption at different points in time (i.e. recalculate the technological, elementary and

576 reference flows of processes). For example, processes concerned by degradation of their performances
577 are marked in blue and processes concerned by occupant behaviour in green – both factors being
578 included in building dynamics DB.

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

590 After the calculation of specific material and energy flows, the system is modelled as for a
591 conventional LCA using e.g. the SimaPro software. This modelling includes many subsystems
592 corresponding to periods with a predefined duration, e.g. 1 year, or 10 years (user defined values),
593 each period being characterized by constant parameters for all processes involved in the period. In
594 other words, the time scale is gridded in order to define periods of constant characteristics. After that,
595 technology (technological flows) and environmental (environmental intervention flows) matrixes are
596 generated by the conventional LCA software and imported into DyPLCA tool. DyPLCA tool adds
597 temporal parameters for the supply chain and environmental interventions, and performs dynamic LCI
598 calculation. The result, in form of environmental interventions distributed in time, is the used for
599 dynamic impact calculation with a Python home-made software.

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

610 performing an environmental assessment with the proposed framework concerns the data collection of
611 building system dynamics since the dynamic approach is new and, obviously, data are lacking.

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

617 Another source of uncertainty on LCA (conventional and dynamic) results is the quality of inventory
618 data obtained from databases, modelling, on-site collection, etc. Besides these quantitative aspects,
619 common for both LCA approaches, the dynamic LCI calculation presents uncertainties related to the
620 time dimension, i.e. specific dynamic behaviour of processes, duration and delays in the supply chain.
621 The new database for building dynamics DB (in figure 1) will contain such time-dependent parameters
622 and their ranges of variation. Sensitivity analysis allows the identification of key parameters of the
623 systems and allowing simulation of plausible scenarios as well as uncertainty estimation.

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

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

637

638 **5. Conclusions**

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

641 The first is *the temporal evolution at the level of the building* itself. Technical performances related to
642 construction products and energy equipment degrade over the long lifetime of buildings. The

643 occupants of a building are thus required to carry out regular maintenance, replacement, and
644 refurbishment of the building system to satisfy a building function. While the degradation of technical
645 performances of buildings needs to be pointed out, it should not be forgotten that technological
646 improvements of construction products and end-user energy systems should also occur because
647 buildings have a lifetime long enough to take advantage of new technologies.

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

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

656 In conclusion of the literature review, a building system is a long life system which evolves in time
657 and for which environmental performance is difficult to assess given the limitations of the commonly
658 used environmental assessment tools. The LCA method has been extensively used for evaluating the
659 environmental impacts of buildings but the lack of a temporal dimension constitutes a considerable
660 limitation. Very few studies have addressed this question so far. Most temporal LCA studies have
661 considered prospective scenarios of technological improvements in fore- and background systems (e.g.
662 energy efficiency of a heating system and cement production) and occupant behaviour (e.g. heating
663 system management) in the long term. Only case studies based in France and the United States have
664 been presented. One study integrated short-term variation of the energy mix composition in LCA,
665 while another showed that it is important to take biogenic CO₂ balance into account over the life cycle
666 of wood-based buildings. The few studies performed so far concerning the building system and its
667 temporal behaviour have proposed an improvement of LCA, which can go beyond the current state of
668 LCA research. However, they do not propose any operational, reproducible tools for performing
669 effective temporal evaluations.

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

674 The life cycle inventory combines an existing environmental dataset for the background processes
675 (ecoinvent v3.2) and LCA software with a new database enabling temporal behaviours of the building
676 system to be parameterized considering technology, occupants, energy mix, and regulations. The
677 DyPLCA tool enables temporal characterizations of processes and supply chains at the background

678 level and for the foreground processes with user-defined temporal parameters. The calculated
679 temporalized LCI is then used in LCIA step to calculate time-dependent environmental impact
680 indicators, i.e. for climate change and toxicity categories. To integrate more specificities of the
681 construction sector, using existing tools and a database specific to the LCA for buildings, e.g.
682 ELODIE (software using FDES as input data) and INIES in France, would help to make dynamic LCI
683 modelling of buildings more case-specific. However, the implementation of dynamic LCA with these
684 specific tools is still limited due to lack of basic information like the elementary flows or too high a
685 degree of data aggregation. Therefore, the next methodological improvement challenges of dynamic
686 LCA for buildings are the exploitation of FDES data to be used in a dynamic LCI calculation, e.g.
687 inclusion of detailed information on inventory data, and the development of a tool to calculate a
688 dynamic LCI based on FDES.

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

697

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701

702 **References**

- 703 [1] B. Peuportier, Life cycle assessment applied to the comparative evaluation of single
704 family houses in the French context, *Energy Build.* 33 (2001) 443–450.
705 doi:10.1016/S0378-7788(00)00101-8.
- 706 [2] G.P. Gerilla, K. Teknomo, K. Hokao, An environmental assessment of wood and steel
707 reinforced concrete housing construction, *Build. Environ.* 42 (2007) 2778–2784.
708 doi:10.1016/j.buildenv.2006.07.021.
- 709 [3] G.A. Blengini, Life cycle of buildings, demolition and recycling potential: A case study
710 in Turin, Italy, *Build. Environ.* 44 (2009) 319–330. doi:10.1016/j.buildenv.2008.03.007.
- 711 [4] R.J. Cole, P.C. Kernan, Life-cycle energy use in office buildings, *Build. Environ.* 31
712 (1996) 307–317. doi:10.1016/0360-1323(96)00017-0.
- 713 [5] K. Adalberth, Energy use during the life cycle of single-unit dwellings: Examples, *Build.*
714 *Environ.* 32 (1997) 321–329. doi:10.1016/S0360-1323(96)00069-8.

- 715 [6] French Ministry of the Environment, Minisère de la Transition Ecologique et Solidaire,
716 (2016). <http://www.batiment-energiecarbone.fr/>.
- 717 [7] JRC European Commission, Level(s): a common EU framework of core sustainability
718 indicators for office and residential buildings : parts 1 and 2, introduction to level(s) and
719 how it works (Beta v1.0)., (2017). [https://publications.europa.eu/en/publication-detail/-](https://publications.europa.eu/en/publication-detail/-/publication/f3c2fc97-f102-11e7-9749-01aa75ed71a1/language-en/format-PDF)
720 [/publication/f3c2fc97-f102-11e7-9749-01aa75ed71a1/language-en/format-PDF](https://publications.europa.eu/en/publication-detail/-/publication/f3c2fc97-f102-11e7-9749-01aa75ed71a1/language-en/format-PDF)
721 (accessed January 12, 2018).
- 722 [8] JRC European Commission, Level(s): a common EU framework of core sustainability
723 indicators for office and residential buildings : part 3, How to make performance
724 assessments using level(s) (Beta v1.0)., (2018).
725 [https://publications.europa.eu/en/publication-detail/-/publication/3bff9f38-f1cc-11e7-](https://publications.europa.eu/en/publication-detail/-/publication/3bff9f38-f1cc-11e7-9749-01aa75ed71a1/language-en/format-PDF)
726 [9749-01aa75ed71a1/language-en/format-PDF](https://publications.europa.eu/en/publication-detail/-/publication/3bff9f38-f1cc-11e7-9749-01aa75ed71a1/language-en/format-PDF) (accessed January 12, 2018).
- 727 [9] CEN, EN 15978:2011, Eur. Comm. Stand. (2011).
- 728 [10] S. Lasvaux, Étude d'un modèle simplifié pour l'analyse de cycle de vie des bâtiments,
729 2012.
- 730 [11] T. de Meester, A.-F. Marique, A. De Herde, S. Reiter, Impacts of occupant behaviours
731 on residential heating consumption for detached houses in a temperate climate in the
732 northern part of Europe, *Energy Build.* 57 (2013) 313–323.
733 doi:10.1016/j.enbuild.2012.11.005.
- 734 [12] J. Toman, A. Vimrová, R. Černý, Long-term on-site assessment of hygrothermal
735 performance of interior thermal insulation system without water vapour barrier, *Energy*
736 *Build.* 41 (2009) 51–55. doi:10.1016/j.enbuild.2008.07.007.
- 737 [13] F. Stazi, F. Tittarelli, G. Politi, C. Di Perna, P. Munafò, Assessment of the actual
738 hygrothermal performance of glass mineral wool insulation applied 25 years ago in
739 masonry cavity walls, *Energy Build.* 68 (2014) 292–304.
740 doi:10.1016/j.enbuild.2013.09.032.
- 741 [14] H.-J. Choi, J.-S. Kang, J.-H. Huh, A Study on Variation of Thermal Characteristics of
742 Insulation Materials for Buildings According to Actual Long-Term Annual Aging
743 Variation, *Int. J. Thermophys.* 39 (2018). doi:10.1007/s10765-017-2318-3.
- 744 [15] Sandrine Marceau, Sabine Caré, Pilar Lesage, *Matériaux Biosourcés et Naturels Pour*
745 *Une Construction Durable*, 2016.
- 746 [16] K. Pommer, C. Pade, Guidelines - Uptake of carbon dioxide in the life cycle inventory of
747 concrete, 2005. [https://www.dti.dk/reports-on-co2-uptake-from-the-carbonation-of-](https://www.dti.dk/reports-on-co2-uptake-from-the-carbonation-of-concrete/guidelines/18487,5)
748 [concrete/guidelines/18487,5](https://www.dti.dk/reports-on-co2-uptake-from-the-carbonation-of-concrete/guidelines/18487,5) (accessed August 10, 2018).
- 749 [17] F. Collins, Inclusion of carbonation during the life cycle of built and recycled concrete:
750 influence on their carbon footprint, *Int. J. Life Cycle Assess.* 15 (2010) 549–556.
751 doi:10.1007/s11367-010-0191-4.
- 752 [18] A. Talon, *Evaluation des scénarii de dégraation des produits de construction*, 2006.
- 753 [19] R. Frischknecht, S. Büsser, W. Krewitt, Environmental assessment of future
754 technologies: how to trim LCA to fit this goal?, *Int. J. Life Cycle Assess.* 14 (2009) 584–
755 588. doi:10.1007/s11367-009-0120-6.
- 756 [20] A. Moro, L. Lonza, Electricity carbon intensity in European Member States: Impacts on
757 GHG emissions of electric vehicles, *Transp. Res. Part Transp. Environ.* (2017).
758 doi:10.1016/j.trd.2017.07.012.
- 759 [21] European Commission, *Energy roadmap 2050*, (2012).
- 760 [22] H. Lund, D. Connolly, B. Vad Mathiesen, P. Alberg Østergaard, B. Möller, S. Nielsen,
761 U. Persson, D. Nilsson, S. Werner, D. Trier, *Heat Roadmap Europe 2050*, (2012).
- 762 [23] France National Low-Carbon Strategy, (2015).
- 763 [24] M. Fouquet, A. Levasseur, M. Margni, A. Lebert, S. Lasvaux, B. Souyri, C. Buhé, M.
764 Woloszyn, Methodological challenges and developments in LCA of low energy

- 765 buildings: Application to biogenic carbon and global warming assessment, *Build.*
766 *Environ.* 90 (2015) 51–59. doi:10.1016/j.buildenv.2015.03.022.
- 767 [25] D. Beloin-Saint-Pierre, A. Levasseur, M. Margni, I. Blanc, Implementing a Dynamic
768 Life Cycle Assessment Methodology with a Case Study on Domestic Hot Water
769 Production, *J. Ind. Ecol.* (2016). doi:10.1111/jiec.12499.
- 770 [26] S. Frijia, S. Guhathakurta, E. Williams, Functional Unit, Technological Dynamics, and
771 Scaling Properties for the Life Cycle Energy of Residences, *Environ. Sci. Technol.* 46
772 (2012) 1782–1788. doi:10.1021/es202202q.
- 773 [27] Fouquet Marine, *Réflexions et contributions méthodologiques à l'ACV de batiments*
774 *neufs : modélisatino du contributeur énergie*, 2015.
- 775 [28] C. Roux, P. Schalbart, B. Peuportier, Accounting for temporal variation of electricity
776 production and consumption in the LCA of an energy-efficient house, *J. Clean. Prod.*
777 113 (2016) 532–540. doi:10.1016/j.jclepro.2015.11.052.
- 778 [29] W.O. Collinge, A.E. Landis, A.K. Jones, L.A. Schaefer, M.M. Bilec, Dynamic life cycle
779 assessment: framework and application to an institutional building, *Int. J. Life Cycle*
780 *Assess.* 18 (2013) 538–552. doi:10.1007/s11367-012-0528-2.
- 781 [30] C. Roux, P. Schalbart, E. Assoumou, B. Peuportier, Integrating climate change and
782 energy mix scenarios in LCA of buildings and districts, *Appl. Energy.* 184 (2016) 619–
783 629. doi:10.1016/j.apenergy.2016.10.043.
- 784 [31] F. Stazi, C. Di Perna, P. Munafò, Durability of 20-year-old external insulation and
785 assessment of various types of retrofitting to meet new energy regulations, *Energy Build.*
786 41 (2009) 721–731. doi:10.1016/j.enbuild.2009.02.008.
- 787 [32] ISO 14040:2006, ISO 14040:2006, *Environ. Manag. - Life Cycle Assess. - Princ.*
788 *Framework. Int. Stand.* (2006a).
- 789 [33] ISO 14044:2006, ISO 14044:2006, *Environ. Manag. - Life Cycle Assess. - Princ.*
790 *Framework. Int. Stand.* (2006a).
- 791 [34] D. Beloin-Saint-Pierre, A. Levasseur, A. Pinsonnault, M. Margni, I. Blanc, How Can
792 Temporal Considerations Open New Opportunities for LCA Industry Applications?, in:
793 6th Int. Conférence Life Cycle Manag., Gothenburg, Sweden, 2013: p. 4 pages.
794 <https://hal-mines-paristech.archives-ouvertes.fr/hal-00920310>.
- 795 [35] P. Collet, L. Lardon, J.-P. Steyer, A. Hélias, How to take time into account in the
796 inventory step: a selective introduction based on sensitivity analysis, *Int. J. Life Cycle*
797 *Assess.* 19 (2014) 320–330. doi:10.1007/s11367-013-0636-7.
- 798 [36] A. Pinsonnault, P. Lesage, A. Levasseur, R. Samson, Temporal differentiation of
799 background systems in LCA: relevance of adding temporal information in LCI
800 databases, *Int. J. Life Cycle Assess.* 19 (2014) 1843–1853. doi:10.1007/s11367-014-
801 0783-5.
- 802 [37] CEN, EN 15804:2012, *Eur. Comm. Stand.* (2012).
- 803 [38] C. Scheuer, G.A. Keoleian, P. Reppe, Life cycle energy and environmental performance
804 of a new university building: modeling challenges and design implications, *Energy*
805 *Build.* 35 (2003) 1049–1064. doi:10.1016/S0378-7788(03)00066-5.
- 806 [39] R. Heijungs, S. Suh, *The Computational Structure of Life Cycle Assessment*, Springer
807 *Netherlands, Dordrecht*, 2002. doi:10.1007/978-94-015-9900-9.
- 808 [40] A. Kendall, Time-adjusted global warming potentials for LCA and carbon footprints, *Int.*
809 *J. Life Cycle Assess.* 17 (2012) 1042–1049. doi:10.1007/s11367-012-0436-5.
- 810 [41] V.P. Shah, R.J. Ries, A characterization model with spatial and temporal resolution for
811 life cycle impact assessment of photochemical precursors in the United States, *Int. J.*
812 *Life Cycle Assess.* 14 (2009) 313–327. doi:10.1007/s11367-009-0084-6.

- 813 [42] A. Levasseur, P. Lesage, M. Margni, L. Deschênes, R. Samson, Considering Time in
814 LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments,
815 Environ. Sci. Technol. 44 (2010) 3169–3174. doi:10.1021/es9030003.
- 816 [43] B. Peuportier, G. Herfray, Evaluation of electricity related impacts using a dynamic
817 LCA model, (2012).
- 818 [44] M. Fesanghary, S. Asadi, Z. W. Geem, Design of low-emission and energy-efficient
819 residential buildings using a multi-objective optimization algorithm, Build. Environ. 49
820 (2012) 245–250. doi:10.1016/j.buildenv.2011.09.030.
- 821 [45] H. Babazadesh, N. Haghighi, S. Asadi, R. Broun, D. Riley, Life cycle assessment of
822 exterior window shadings in residential buildings in different climate zones, Build.
823 Environ. 90 (2015) 168–177. doi:10.1016/j.buildenv.2015.03.038.
- 824 [46] S. Su, X. Li, Y. Zhu, B. Lin, Dynamic LCA Framework for Environmental Impact
825 Assessment of Buildings, Energy Build. (2017). doi:10.1016/j.enbuild.2017.05.042.
- 826 [47] S. BORDEBEURE, Déchet du Bâtiment, 2017.
- 827 [48] L. Tiruta-Barna, Y. Pigné, T. Navarrete Gutiérrez, E. Benetto, Framework and
828 computational tool for the consideration of time dependency in Life Cycle Inventory:
829 proof of concept, J. Clean. Prod. 116 (2016) 198–206.
830 doi:10.1016/j.jclepro.2015.12.049.
- 831 [49] A.H. Shimako, L. Tiruta-Barna, Y. Pigné, E. Benetto, T. Navarrete Gutiérrez, P.
832 Guiraud, A. Ahmadi, Environmental assessment of bioenergy production from
833 microalgae based systems, J. Clean. Prod. 139 (2016) 51–60.
834 doi:10.1016/j.jclepro.2016.08.003.
- 835 [50] A.H. Shimako, L. Tiruta-Barna, A. Ahmadi, Operational integration of time dependent
836 toxicity impact category in dynamic LCA, Sci. Total Environ. 599–600 (2017) 806–819.
837 doi:10.1016/j.scitotenv.2017.04.211.
- 838 [51] A.H. Shimako, L. Tiruta-Barna, A.B. Bisinella de Faria, A. Ahmadi, M. Spérandio,
839 Sensitivity analysis of temporal parameters in a dynamic LCA framework, Sci. Total
840 Environ. 624 (2018) 1250–1262. doi:10.1016/j.scitotenv.2017.12.220.
- 841 [52] IPCC, ed., Climate Change 2013 - The Physical Science Basis: Working Group I
842 Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate
843 Change, Cambridge University Press, Cambridge, 2013.
844 doi:10.1017/CBO9781107415324.
- 845 [53] M.Z. Hauschild, M. Huijbregts, O. Jolliet, M. Macleod, M. Margni, D. van de Meent,
846 R.K. Rosenbaum, T.E. McKone, Building a Model Based on Scientific Consensus for
847 Life Cycle Impact Assessment of Chemicals: The Search for Harmony and Parsimony,
848 Environ. Sci. Technol. 42 (2008) 7032–7037. doi:10.1021/es703145t.
- 849 [54] R.K. Rosenbaum, T.M. Bachmann, L.S. Gold, M.A.J. Huijbregts, O. Jolliet, R. Juraske,
850 A. Koehler, H.F. Larsen, M. MacLeod, M. Margni, T.E. McKone, J. Payet, M.
851 Schuhmacher, D. van de Meent, M.Z. Hauschild, USEtox—the UNEP-SETAC toxicity
852 model: recommended characterisation factors for human toxicity and freshwater
853 ecotoxicity in life cycle impact assessment, Int. J. Life Cycle Assess. 13 (2008) 532–
854 546. doi:10.1007/s11367-008-0038-4.
- 855 [55] A. Shimako, Contribution to the development of a dynamique Life Cycle Assessment
856 method, Thesis report, INSA Toulouse, 2017.
- 857 [56] Commissariat général au développement durable, Durée de construction des logements:
858 le rôle des tensions dans l'industrie du bâtiment entre 1990 et 2010, 2012.
859