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Dynamic Life Cycle Assessment - Parameters for scenario development in prospective environmental modelling of building stocks

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Abstract. The global climate crisis calls for the urgent decrease of life cycle environmental impacts of building stocks. However, due to the long life spans of buildings, the complexity of prospective environmental modelling increases, compounded by uncertainty. While dynamic life cycle assessment (DLCA) is able to incorporate temporal variations of parameters (e.g. energy mix) or processes (e.g. technological improvement), their modelling methods have not yet been systematically analysed. This review paper aims to identify the typical dynamic parameters applied in building stock modelling, and advance the understanding of methods for predicting the associated temporal evolutions. We searched for publications on Science Direct database and collected 102 papers. A representative sample of 12 papers was then selected and analysed in detail. The results include 8 typical dynamic parameters and 5 methods for predicting the evolutions. We discuss the limitations of each parameter and formulate some recommendations. Presented research may help produce standardised evolution scenarios which, in turn, will help quantify the environmental impacts of building stocks in a more consistent manner, and inform design decisions that yield improved life cycle performance.

1. Introduction

Buildings have a major role in effectively addressing climate change. Globally, buildings are responsible for at least 38% of total energy-related carbon dioxide emissions [1] while in the European Union, the built environment is recognised as single largest energy user [2]. As buildings cause environmental impacts throughout their life cycle, the pressing nature of climate crisis calls for life cycle impact assessment on larger scales, such as building stocks. Such impacts may be quantified with life cycle assessment (LCA), which is an internationally standardised method [3, 4] that evaluates potential environmental impacts occurring from the extraction of raw materials to the end-of-life phases. However, the main limitation of LCA is the omission of changes in the parameters affecting environmental impacts over time [5-7]. This is particularly critical in the case of buildings which last decades, and sometimes centuries. For example, if a high amount of pollutants is released during the construction stage, it will not have the same environmental impact compared to spread out emissions across time, as impacts vary with changes in atmospheric composition [8, 9]. As such, the absence of temporal data may significantly affect the reliability and accuracy of life cycle assessment results.

Dynamic life cycle assessment (DLCA) explicitly recognizes the importance of timing in the assessment of potential environmental impacts, and integrates the evolving nature of the assessed system into the modelling framework. Review papers have already recognised DLCA as a research direction. However, they are limited to specific parameters, such as carbon dioxide sequestration and emissions [6, 10, 11], or focused on environmental modelling from urban to transnational scales, only providing some examples of the dynamic aspects, without systematically analysing them [12, 13]. While review papers specifically addressing temporal parameters in DLCA modelling framework [5, 14-16] have been published, none of them have investigated methods for predicting temporal evolutions of parameters. In this paper, an evolution in DLCA is defined as variation of a parameter or a process, retrospectively or prospectively, as function of time, in form of hypotheses with defined trends, based on existing data or what-if scenarios. Also, the term building stock is used to describe all buildings belonging to a neighbourhood, a city, or any other collection of buildings.

This paper explores the following two research questions: (a.) What are the dynamic parameters applied in studies of prospective DLCA modelling of building stocks? (b.) What are the methods applied for predicting the temporal evolutions of parameters? As such, this paper aims to review research articles on DLCA, identify typical parameters used in modelling building stocks, and investigate methods for predicting the associated temporal evolutions.

The structure of the paper comprises 5 sections. Following the Introduction, Section 2 describes the review methodology. Selected sample of studies and analysed evolving parameters are presented in Section 3. Limitations and recommendations are discussed in Section 4. Finally, Section 5 concludes the paper.

2. **Dynamic life cycle assessment in the literature - methodology**

This section presents a method for collecting and analysing a representative sample of articles that are studying or applying DLCA and temporal evolutions of parameters. We conducted the search on the Scopus database, limiting results to available review articles, original research articles and conference papers, published from 2012 until February 2022. The search was conducted within titles, abstracts and author-specified keywords and limited to papers written in English. Query strings were formulated by combining keywords through an iterative process. The search keywords included, but were not limited to, the following three lists: (a.) dynamic life cycle assessment, dynamic life cycle analysis, dynamic LCA, DLCA, (b.) dynamic, time-dependent, time-varying, temporal, parameter, evolution, variable, variation, consideration, aspect, and (c.) building stock, buildings.

An example of a query string is [("dynamic life cycle assessment" OR "dynamic life cycle analysis" OR "dynamic LCA" OR DLCA) AND (buildings OR "building stock")]. The initial subsample of articles was documented in an EndNote library and comprised citation information, abstracts and keywords. A subsample was refined through the screening of titles and abstracts. We kept the articles that met the following criteria: (a.) prospective studies, (b.) studies applying DLCA methods (c.) studies including at least one evolving parameter, e.g. energy mix, and (d.) studies that are not duplicates of existing research.

In parallel, the subsample was continuously enlarged through snowballing and reference exchanges with colleagues. This process identified 102 articles, out of which, 19 are review articles, 71 research articles and 12 conference papers. The full text of each article was screened for the dynamic parameters and methods for obtaining the associated evolutions. A final sample of 12 articles was selected manually for the purpose of this conference paper, in order to represent a good coverage of different temporal evolution of parameters. Some parameters were omitted from the literature review, due to the mismatch in scope (e.g. decay rate of air pollutants or climate-related changes). Data were extracted from the selected sample, in order to document information about the article (authors, year of publication), presented study (scale, assessed object and temporal scope), and dynamic parameters (methods, sources and evolutions). We systematised the data in two tables characterising each article and each evolving parameter.

It is important to highlight that the scope of this conference paper is limited to 12 articles on purpose, due to space restrictions. Each selected article was a subject of internal discussions of co-authors. Papers that are not considered representative are tagged and excluded from the final sample. Reasons for exclusions are documented. A full review of all papers will be published in a journal article.

3. Dynamic parameters and methods for predicting associated evolutions

Overall, the results presented below reveal 8 dynamic parameters. The highest number of parameters addressed in a single study is 5, by Negishi et al. [17] and by Sandberg and Brattebø [18]. Studies are modelling on average 3 parameters. A summary of the analysed publications is presented in Table 1.

Studies are conducted on eight scales ranging from building element (e.g. wooden panel) to international, but typically focusing on a national (3 of 12 studies) or neighbourhood scale (3). The results show 9 building types assessed, focusing mostly on residential (8). Only 3 studies included more than one building type. Building stocks are usually aggregated using an archetype approach (9), that is described in [12]. The temporal scope typically covers periods of analysis (the effective period of time over which a built stock is modelled) that start in the year of the study, and end in 2050 (aligned with strategies for achieving carbon neutral economies, i.e. ~30-50 years). Time horizons, which are defined as the time over which environmental impacts are modelled, can be extended to a maximum of 500 years.

The dynamic parameters that are most often addressed include stock development (in 6 studies), energy mix (6) and technological development (6), followed by biogenic carbon (5), carbonation (3), occupants (3) and population growth (3), and finally degradation of materials and systems (1). Results show that the stock development mobilises the highest number of parameter types, that comprise new construction, replacement, renovation, retrofit and demolition. Summary of dynamic parameters is presented in Table 2.

The evolutions are based on one or more modelling methods, and are developed and/or applied 32 times in total. The evolutions are most often based on a single method: hypotheses in deterministic (10 of 32) and probabilistic (7) modelling, followed by parametric modelling through mathematical equations (4), interpolation based on existing data and extrapolation (3), output evolution modelled as function of input evolutions (1), or on a combination of two (4) or even three (2) methods. Lack of data about the applied method is observed once (1).

Table 1. Summary of analysed publications

Ref	Authors	Year	Scale	Occupants		Energy mix		Technological improvement		Degradation of materials and syst.		Biogenic carbon		Concrete carbonation		Stock development		Population growth	
				M	R	M	R	M	R	M	R	M	R	M	R	M	R	M	R
[19]	Göswein et al.	2021	AR			HD, E	A, T, P					X	S, T						
[20]	Cherubini et al.	2012	EL									HP, E	A						
[21]	Heeren and Hellweg	2018	NT													HP, HD, O	A, D	I	D
[22]	Heeren et al	2013	C			HD	P	E	S							E	A, D		
[23]	Lausselet et al.	2020	NG			HD	P												
[24]	Lausselet et al.	2021	NG					HD	A							HP	A		
[17]	Negishi et al.	2019	B			HD	P	HD	A	HD	A, S	HP	X	HP	S				
[25]	Pittau et al.	2019	IN									E	A, S	E	A, S				
[26]	Resch et al.	2021	PF					HP	A			HP	A	HP	A	HP	A		
[18]	Sandberg and Brattebø	2012	NT	I, HD	D	HD	A, N	HD	A							O	A, P	I	D
[27]	Sandberg et al.	2014	NT	I, HD	D											E, O, I	A, D	I	D
[28]	Stephan et al.	2013	NG			HD	A, S	HD	A, S										

Note: M = Method; R = Reference; Scale: IN = International; NT = National; C = City; NG = Neighbourhood; PF = Portfolio; AR = Area; B = Building; EL = Element; Method: HP = Hypothesised evolutions, probabilistic model; HD = Hypothesised evolutions, deterministic model; E = Detailed parametric modelling through mathematical equations; O = Output evolution modelled as function of input evolution(s); I = Interpolation based on existing data (retrospective) and extrapolation (prospective); Reference: A = Developed by authors; S = Reference from separate scientific studies; T = Reference to open-source online tool; P = In line with policy targets and/or based on projections; D = According to existing data, e.g. statistics or surveys; N = Reference to standards and norms; X = Partially explained, lack of information; Shaded = Not modelled.

Table 2. Summary of dynamic parameters

Parameter category	Parameter type	Assessed objects	Scale	POA	TH	Method for evolving the parameter	Evolutions	Ref
Building stock development	Demolition, refurbishment	Residential buildings stock building-by-building	NT	2015-2055	100	Probabilistic, assessing buildings lifetime, refurbishment years and one of six refurbishment scenarios. Authors reference existing data from the Swiss Federal Register of Buildings and Dwellings, such as year of construction, and previous studies.	Probability density function, Weibull and conditional Weibull.	[21]
	Construction	Residential buildings stock building-by-building	NT	2015-2055	100	New constructions area modelled as a function of demand for new space due to population growth and demolished buildings. Referencing population projections of Swiss Federal Office for Statistics.	Dependent projection	[21]
	Construction, renovation, retrofit, demolition	Building stock,13 cohorts, archetypes	C	2005-2050	-	Projections for future stock based on demographic projections, household size assumptions, diffusion rates and growth functions. Parametric modelling, mathematical equations developed by authors, published in earlier study. Retrofit rates referenced. Effective retrofit rate, as a share of thermally improved building components in a certain period of time. Retrofit rates referenced from separate studies and survey data.	Dependent projection	[22]
	Construction, renovation, demolition	School, kindergarten, 625 houses, archetypes	NG	2019-2080		Model referenced from separate study by authors (Sandstad et al. 2018). Probabilistic modelling, for timing of future renovation and demolition activities	Normal probability distribution	[24]
	Replacement	20 buildings, 9 types, building-by-building	PF	100	100	Probabilistic, assessing product replacement times. Years of future emissions represented by a random variable with increasing variance. No cut-off allocation model. Hypothesized service life od product.	Normal distribution, chi-square distribution, and discrete approach	[26]

Parameter category	Parameter type	Assessed objects	Scale	POA	TH	Method for evolving the parameter	Evolutions	Ref
	Construction, renovation, demolition	Residential building stock, cohorts, archetypes	NT	1800-2100	300	Output evolutions of floor area inflows, outflows and cumulative changes obtained through multiple input evolutions: population growth, persons per dwelling, floor area per dwelling and lifetime of the buildings, based on previous work from the authors (Bergsdal et al. 2007).	Interpolated trend line	[18]
	Construction, renovation, demolition	Residential building stock, 5 cohorts, 10 archetypes	NT	2010-2050	400	Construction, renovation and demolition rate (output evolutions). Demand for dwellings, as function of population growth and number of persons per dwelling (input evolutions). Lifetime profile of buildings, three renovation profiles with average cycle length, two demolition profiles.	Cyclic repetition of normal distribution, Weibull and normal probability functions.	[27]
Electricity mix		Residential building stock, 8 archetypes	A	2020-2050	100, 200	Emission intensity reduction in line with Portuguese Carbon Neutrality Roadmap by 2050. Scenario based on online tool Transition Pathway Explorer (http://tool.european-calculator.eu/).	Decreasing exponential function, decreasing quadratic function	[19]
		Building stock, 13 cohorts, archetypes	C	2005-2050	-	Electricity production mix modelled for two scenarios: business-as-usual and efficient, following assumptions made by the city electricity provider.	Stacked column charts	[22]
		20 residential buildings, 1 archetype	NB	2012-2050	-	Decarbonization of the electricity mix, projections for 6 °C, 4 °C and 2 °C scenarios in EU by 2050. Energy Technology Perspectives scenarios referenced from International Energy Agency (IEA 2015).		[23]
		3 residential buildings, archetype	B	2015-2065	100	Evolution of the French electricity mix referenced from (ADEME, 2017). Energy mix in 2010 develops through two scenarios, each defined by the share of nuclear, gas and renewable sources in 2035 and 2065. Technological progress not considered.	Stacked column chart	[17]
		Residential building stock, cohorts, archetypes	NT	2000-2050		Linear change in distribution of energy carriers (Bøeng 2005), three scenarios for CO2 emission intensity for electricity generation: two energy mixes are constant and third assumed to linearly decrease.	Linear decrease, linear increase	[18]
		Residential building stock, archetypes	NG	100		Evolution referenced from separate study (IEA 2011), and assumed by authors. Reduction of primary energy and GHG emission conversion factors for electricity due to installation of renewable energy sources.	Cubic interpolation	[28]
Biogenic carbon		Residential building, 8 archetypes	A	2020-2050	100, 200	Temporal distribution computed with LCA software dynco2, (https://ciraig.org/index.php/project/dynco2-dynamic-carbon-footprinter/) Benefits of carbon uptake of re-growing plants accounted to lca stage B5		[19]
		Wood, 3 uses	EL	Up to 500	20, 100, 500	Carbon uptake in growing forest modelled with Schnute model (1981). Carbon release presented with multiple probability distributions.	Delta function, uniform, exponential, chi-squared distributions	[20]
		3 residential buildings, archetype	B		250	Biogenic carbon uptake accounting: trees grow before the use of product. Calculation method, lack of information.		[17]
		Residential building stock, 7 geo-clusters, archetypes	IN	2018-2218	200	Dynamic LCA model based on method developed by Levasseur et al. (2010, 2012). Uptake accounted to stage B1 Use i.e. Forest and crops regrow after harvesting.		[25]
		20 buildings, 9 types, building-by-building	PF	100	100	Attribution of uptake to regrowth of trees after the harvest. Release, assumption: 50% of total amount stored is released at the end of life cycle.	Chapman–Richards growth function	[26]
Carbonation		Residential building stock, 7 geo-clusters, archetypes	IN			Fick's first law of mono-directional diffusion of carbonation, model developed by (Van Balen, Van Gemert 1994). Speed factors for mortars, hempcrete products and concrete-based materials assumed according to the material porosity, lime content and exposition, values referenced from (Xi et al. 2016, Arrigoni et al. 2017). Carbon uptake accounted to use phase B1.		[25]
		20 buildings, 9 types, building-by-building	PF	100		Authors report lack of detailed data, e.g exposure to air of cement-based materials. Hypothesis of 0.1 kgCO_2 uptake per kg cement over 100 years.	Exponential decay function	[26]

Parameter category	Parameter type	Assessed objects	Scale	POA	TH	Method for evolving the parameter	Evolutions	Ref
Technological improvement	Appliances	Building stock 13 cohorts, archetypes	C	2005-2050		Bass model (1969), formula that describes technology diffusion rates for ventilation and heating systems on markets. Methods to determine the diffusion of household appliances (Mcneil and Letschert 2010) and future energy demand of household appliances (Tao and Yu 2011, Shade et al. 2009) in residential sector are combined with specific energy demand, market diffusion rate, and product lifetime to project future market distribution and household energy demand.	Dependent projection	[22]
	Construction materials	School, kindergarten, 625 houses, archetypes	NG	2019-2050		Improving yield in production with direct effect on materials' emission intensities. Method published in other study by authors (Resch et al. 2020).	Linear decrease	[24]
	Construction materials	3 residential buildings, archetype	B	2015-2065	100	Function assumed by authors, according to expert opinion. Electricity consumption reduction of 10% every decade was considered for most energy consuming processes for construction product fabrication function.	Linear decrease	[17]
	Construction materials, PV panels, waste processing, transport	20 buildings, 9 types, building-by-building	PF	100		Method previously developed by authors in (Resch et al. 2020). Technological progress is implemented by weighing the probability distributed future emissions by exponential decay functions starting in the year of construction. ~1% yearly improvement for production of building materials, ~1% for waste processing, 2% for transport, 3.7% t for production of PV panels.	Exponential decay function	[26]
	Heating, DHW electrical appliances, construction materials	Residential building stock, cohorts, archetypes	NT	2000-2050		Energy intensity for heating and DHW assumed to reduce linearly, due to energy conservation and efficiency policies. Energy intensity for use of electrical appliances assumed to remain constant, as increased energy efficiency is assumed to be offset by the trend of more electric appliances per area. Energy intensities for materials production based on predictions for material density per m2 (Bergsdal et al. 2007) and 10% reduction in energy use per ton of produced material.	Linear decrease	[18]
	Appliances	Residential building stock, archetypes	NG	100		Increase and decrease of appliances energy demand by 50%. Based on estimates (DEWHA 2008) and survey data (IEA 2005). Decrease projects technological improvement in energy efficiency of appliances.	Cubic interpolation	[28]
Degradation of materials and systems		3 residential buildings, archetype	B	2015-2065	100	Degradation rates for insulation thermal performance, airtightness, heating and hot water systems taken from literature and estimated at 1 year time step. Decrease of heat transfer coefficient for each insulation type not clear.	Repetitive linear decrease	[17]
Occupants		3 residential buildings, archetype	B	2015-2065	100	Adequate number of adults as function of building area. Based on national statistics, and thermal regulations of buildings.		[17]
		Residential building stock, 5 cohorts, 10 archetypes	NT	1800-2050	250	Based on national statistics (Statistics Norway 2013, 2005), the average number of persons per dwelling has decreased from 1800 to 2011, by minor further decrease in 2050. Distribution per detached or compact dwellings according to census data. Assumed by authors. Input evolution.	Linear interpolation, sigmoidal non-linear regression	[18, 27]
Population growth		Residential stock, building-by-building	NT	2015-2055	100	Population projections according to the scenario A-00-2015 from statistical data (Swiss Federal Office for Statistics 2015). Input evolution.	Linear interpolation between observation points	[21]
		Residential building stock, archetypes	NT	1800-2050	150, 250	Population projection according to the medium scenario from statistical data (Statistics Norway 2013). Input evolution.	Linear interpolation between observation points	[18, 27]

Notes: IN = International; NT = National; C = City; NG = Neighbourhood; PF = Portfolio; AR = Area; B = Building; EL = Element; X = Partially explained, lack of information; References cited in the analysed papers are not included in the Reference section of this paper, due to the space restrictions, but the authors and years of publication are provided.

4. Discussion

4.1. Limitations and recommendations for each parameter

The development of the building stock encompasses one or more parameter types, such as future construction or renovation. This suggests that studies which, for example, omitted the process of material replacement, did not cover the phase B4 as defined in EN-15978 [29], thus limiting the analysis of overall dynamic of building stocks. We found that all five methods analysed in this paper are applied for modelling the evolutions of building stocks. For example, some methods rely heavily on demographic projections, household size assumptions, number of persons living in a building or size of a building. Such number of input projections results in high uncertainties. As such, we recommend that modelling frameworks should allow a high degree of flexibility in testing different evolution values in a simplified manner, so that the sensibility of results to particular parameters can be identified.

In contrast, electricity mix modelling methods tend to be developed in a more consistent manner. The reason may be that most of the studies rely on decarbonisation strategies developed by international agencies (e.g. IEA) or national carbon neutrality roadmaps. The limitation is that such approach inherently leads to the year 2050 and assumes achievement of carbon emission targets through relatively short-term projections. Also, current projections are not able to account for the uncertainties (e.g. current political instabilities at an international level) that can dramatically affect energy mixes. We recommend higher flexibility of model frameworks, and extension of the temporal scope to enable the application of evolutions over long periods of time.

Biogenic carbon modelling frameworks account for carbon stored in harvested plants used for production of bio-based materials (e.g. timber), which seems to yield inconsistent results due to the allocation of the storage period before or after the harvest. While our limited sample of papers does not aim at mapping all available models for biogenic carbon accounting, it was still challenging to report modelling approaches, as many authors did not describe their biogenic carbon model in detail. Thus, we call for additional transparency in reporting the applied modelling methods for parameter evolutions, following best practice in industrial ecology [30].

Carbonation is considered in only two analysed studies. The reported limitation is the lack of detailed data on lime-based materials, such as the surface area exposure to the ambient air during the use of buildings [26]. However, only the minor carbonation of less than 2% is established during this phase. After crushing, when the element is used as a recycled aggregate, a significant 20% carbon uptake can take place [31, 32]. Our recommendation is to clearly define and standardise the scope, in terms of LCA phases covered. If allocated to the use (phase B1), given the lower significance of carbonation on the life cycle greenhouse gas emissions of building stocks as compared to other dynamic parameters, we recommend that it be left as the lower priority in the dynamic life cycle assessment of buildings.

The evolutions of technological processes appear to be modelled consistently, through deterministic or probabilistic hypotheses developed by the authors. However, it is important to highlight the heterogeneity of parameter types i.e. electrical appliances (efficiency, distribution, use), domestic hot water production, heating, and production of construction materials. Thus, we recommend further research to clarify the scope and integrate the synergies between changes in the electricity mix and technological development.

Degradation of materials and systems is addressed only in one analysed study. We underline the importance of adequate reporting of the referenced data and modelling methods. A larger sample of studies is necessary to discuss the degradation of materials and systems over time.

Occupants and population growth are parameters that are often used as input evolutions for modelling of the residential stock development over time. The occupants parameter remains limited to the residential building type, and mainly relies on national statistical data and relating projections. We recommend extending the scope from residential to other building types, such as offices, educational or medical buildings. This may also require further research, to formulate new evolving parameters, such as changes of occupancy rates or changes in building functions (e.g. schools to hospitals or shelters).

4.2. Relation to other studies

To the best of our knowledge, 1 research and 3 review articles systematise dynamic parameters in LCA.

Negishi et al. [16] propose a DLCA methodology for buildings, and document 12 characteristics of a building system that should be integrated into the LCA method. Dynamic parameters, named "characteristics of building system" in [16], that are not included in our study are: thermal comfort level, integration of renewable energy systems, and improved recycling rate.

Su et al. [14] present 3 typical assessment models for buildings, and 11 dynamic variables in building life cycle. The four following variables were not identified within our study: end of life stage of components and devices, temperature change, waste recycling rates and characterisation factor.

Beloin-Saint-Pierre et al. [5] review the temporal considerations in LCA methodology and provide valuable insights on how and where to include them in the modelling framework i.e. goal and scope definition, inventory analysis or impact assessment. Temporal consideration, defined as any aspect that relates to the dimension of time or dynamics of systems in LCA, thus differs from the definitions of parameter and temporal evolution analysed in our study. An example of temporal consideration in [5] is a Dynamic functional unit, systematised in subsection "Modelling choices" of section "Goal scope definition".

Lueddeckens et al. [15] review temporal issues, based on the ISO 14040 standard [3], and systematise them in 6 types: time horizon, discounting, temporal resolution of the inventory, time-dependent characterisation, dynamic weighting, and time-dependent normalisation. Even though the authors suggest valuable solutions for temporal issues in LCA modlling framework, they do not address dynamic parameters analysed in our study.

It is important to highlight that none of the above articles have investigated methods used to predict the temporal evolution of parameters, which are paramount to the rigour and robustness of the evolutions and associated results.

4.3. Limitations

Our literature review has a number of limitations. Firstly, the selected sample of analysed studies is restricted in size, which in turn provides limited variation of evidence of modelling methods and evolutions of certain parameters. Moreover, extracted data types are incomplete and do not cover all types of data in a life cycle assessment framework, i.e. input data for definition of goal, scope, life cycle inventory and impact assessment. It is also important not to overlook other methods applied in the analysed studies, such as material stocks and flow analysis [24] or geographic information systems [21]. Indeed, dynamic modelling of inflows, stock and outflows of resources (e.g. mass of timber) in building stocks over time, and direct link with the two- or three-dimensional data (e.g. building footprints or geometries) at urban scales, may provide more robust data and decrease the uncertainty in modelling dynamic parameters (e.g. biogenic carbon or stock development).

5. Conclusion and recommendations

In this paper we presented a review of the key parameters in prospective building stocks modelling, and methods for predicting associated temporal evolutions. We deeply analysed a sample of 12 representative studies. Our review identified the following dynamic parameters: building stock development, electricity mix, biogenic carbon, carbonation, technological improvement, degradation of materials and systems, occupants and population growth. We analysed their parameter types and the methods for predicting associated temporal evolutions: hypotheses in deterministic and probabilistic modelling, detailed parametric modelling through mathematical equations, output evolution modelled as function of input evolutions and, interpolation according to existing data and extrapolation. Finally, we offer some recommendations for the DLCA modelling of building stocks:

- Modelling frameworks should allow high flexibility in defining and testing different hypothesised scenarios in a simplified manner.

- Standardised and synchronised methods for obtaining evolutions should be developed for each parameter, in order to be able to apply them in different contexts and reach comparable results.
- Temporal scope should be extended and clearly defined, to enable the application of standardised evolutions over long periods of time.
- The topic of interdependence identified between parameters should be further researched.
- Authors should strive for high transparency in reporting about the developed or referenced modelling methods and data.

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Authors contributions

KS collected, screened and analysed the final sample of articles. KS wrote the first draft of the paper and created tables with the consultation of AS and GM. AS and GM reviewed the paper and provided comments.

References

[1] 2022 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. (Nairobi: Global Alliance for Buildings and Construction (GABC), International Energy Agency (IEA), United Nations Environment Programme (UNEP))
[2] 2020 In focus: Energy efficiency in buildings. European Comission (EC))
[3] 2006 ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization)
[4] 2006 ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. International Organization for Standardization)
[5] Beloin-Saint-Pierre D, Albers A, Hélias A, Tiruta-Barna L, Fantke P, Levasseur A, Benetto E, Benoist A and Collet P 2020 Addressing temporal considerations in life cycle assessment *Science of The Total Environment* **743** 140700
[6] Arehart J H, Hart J, Pomponi F and D'Amico B 2021 Carbon sequestration and storage in the built environment *Sustainable Production and Consumption* **27** 1047-63
[7] Su S, Li X, Zhu Y and Lin B 2017 Dynamic LCA framework for environmental impact assessment of buildings *Energ Buildings* **149** 310-20
[8] Levasseur A, Lesage P, Margni M, Deschênes L and Samson R 2010 Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments *Environmental Science & Technology* **44** 3169-74
[9] Levasseur A, Lesage P, Margni M, Brandão M and Samson R 2012 Assessing temporary carbon sequestration and storage projects through land use, land-use change and forestry: comparison of dynamic life cycle assessment with ton-year approaches *Climatic Change* **115** 759-76
[10] Breton C, Blanchet P, Amor B, Beauregard R and Chang W S 2018 Assessing the climate change impacts of biogenic carbon in buildings: A critical review of two main dynamic approaches *Sustainability (Switzerland)* **10**
[11] Hoxha E, Passer A, Saade M R M, Trigaux D, Shuttleworth A, Pittau F, Allacker K and Habert G 2020 Biogenic carbon in buildings: a critical overview of LCA methods *Buildings and Cities* **1** 504-24
[12] Mastrucci A, Marvuglia A, Leopold U and Benetto E 2017 Life Cycle Assessment of building stocks from urban to transnational scales: A review *Renew Sust Energ Rev* **74** 316-32
[13] Röck M, Baldereschi E, Verellen E, Passer A, Sala S and Allacker K 2021 Environmental modelling of building stocks – An integrated review of life cycle-based assessment models to support EU policy making *Renew Sust Energ Rev* **151** 111550
[14] Su S, Zhang H, Zuo J, Li X and Yuan J 2021 Assessment models and dynamic variables for dynamic life cycle assessment of buildings: a review *Environmental Science and Pollution Research* **28** 26199-214
[15] Lueddeckens S, Saling P and Guenther E 2020 Temporal issues in life cycle assessment—a systematic review *Int J Life Cycle Ass* **25** 1385-401

[16] Negishi K, Tiruta-Barna L, Schiopu N, Lebert A and Chevalier J 2018 An operational methodology for applying dynamic Life Cycle Assessment to buildings *Building and Environment* **144** 611-21

[17] Negishi K, Lebert A, Almeida D, Chevalier J and Tiruta-Barna L 2019 Evaluating climate change pathways through a building's lifecycle based on Dynamic Life Cycle Assessment *Building and Environment* **164** 106377

[18] Sandberg N H and Bratteb H 2012 Analysis of energy and carbon flows in the future Norwegian dwelling stock *Build Res Inf* **40** 123-39

[19] Göswein V, Silvestre J D, Sousa Monteiro C, Habert G, Freire F and Pittau F 2021 Influence of material choice, renovation rate, and electricity grid to achieve a Paris Agreement-compatible building stock: A Portuguese case study *Building and Environment* **195** 107773

[20] Cherubini F, Guest G and Strømman A H 2012 Application of probability distributions to the modeling of biogenic CO2fluxes in life cycle assessment *GCB Bioenergy* **4** 784-98

[21] Heeren N and Hellweg S 2018 Tracking Construction Material over Space and Time: Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows *Journal of Industrial Ecology* **23** 253-67

[22] Heeren N, Jakob M, Martius G, Gross N and Wallbaum H 2013 A component based bottom-up building stock model for comprehensive environmental impact assessment and target control *Renew Sust Energ Rev* **20** 45-56

[23] Lausselet C, Ellingsen L A W, Strømman A H and Brattebø H 2020 A life-cycle assessment model for zero emission neighborhoods *Journal of Industrial Ecology* **24** 500-16

[24] Lausselet C, Urrego J P F, Resch E and Brattebø H 2021 Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock *Journal of Industrial Ecology* **25** 419-34

[25] Pittau F, Lumia G, Heeren N, Iannaccone G and Habert G 2019 Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock *J Clean Prod* **214** 365-76

[26] Resch E, Andresen I, Cherubini F and Brattebø H 2021 Estimating dynamic climate change effects of material use in buildings—Timing, uncertainty, and emission sources *Building and Environment* **187** 107399

[27] Sandberg N H, Sartori I and Brattebø H 2014 Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock *Energy and Buildings* **82** 287-95

[28] Stephan A, Crawford R H and de Myttenaere K 2013 Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia *Building and Environment* **68** 35-49

[29] 2011 EN 15978:2011 Sustainability of construction works—Assessment of environmental performance of buildings — Calculation method.: European Committee for Standardization (CEN))

[30] Hertwich E, Heeren N, Kuczenski B, Majeau-Bettez G, Myers R J, Pauliuk S, Stadler K and Lifset R 2018 Nullius in Verba1: Advancing Data Transparency in Industrial Ecology *Journal of Industrial Ecology* **22** 6-17

[31] Saade M R M, Guest G and Amor B 2020 Comparative whole building LCAs: How far are our expectations from the documented evidence? *Building and Environment* **167**

[32] Collins F 2010 Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint *The International Journal of Life Cycle Assessment* **15** 549-56