ESSENTIAL PARAMETERS IN STEPWISE RETROFITTING FOR LONG-TERM EMISSION REDUCTION IN RESIDENTIAL BUILDINGS

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Stepwise retrofitting is significant for sustaining thermal comfort and energy efficiency in residential buildings long-term. However, existing models on stepwise retrofitting have ignored the social parameters while overlooking the temporal variations of many parameters. Thus, the study aims to investigate essential temporal parameters for timing stepwise retrofitting to maximise long-term emission reduction in existing residential buildings. The parameters were identified across environmental, technical, social, and economic categories through a comprehensive process, which included a desk study and nine expert interviews, followed by a thematic analysis. The findings revealed the applicability of novel parameters for stepwise retrofitting, including temporal variations of embodied and operational emissions, minimum call-out fee, market value, homeowner willingness, and point of sale, rental, and refurbishment intervals. Practitioners can use the determined parameters for long-term emission reduction through stepwise retrofitting, following validation in real case studies. These parameters will assist in developing a comprehensive dynamic model to estimate the optimal timing between steps in stepwise retrofitting, maximising long-term emission reduction.

Keywords: long-term emission reduction; stepwise retrofitting; social parameters; sustainable housing; temporal parameters

INTRODUCTION

The building industry plays a pivotal role in achieving energy and climate policy objectives, as buildings account for 30% of the global final energy demand, with residential buildings contributing to over two-thirds of this share (IEA 2023). Thus, existing housing stock should undergo necessary modifications, known as retrofitting, to enhance energy efficiency (Liu *et al.,* 2021).

With a few exceptions, global policies and research on retrofitting generally overlook the timing of its implementation. They often assume implementing all proposed retrofit measures simultaneously, known as the single-step approach, will be sufficient for decarbonisation (Maia *et al.,* 2021). Although the single step retrofitting method offers two significant benefits, including (i) fast emission reduction once retrofitted

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Hulathdoowage, N D, Karunasena, G, Udawatta, N and Liu, C (2024) Essential Parameters in Stepwise Retrofitting for Long-Term Emission Reduction in Residential Buildings *In:* Thomson, C and Neilson, C J (Eds) *Proceedings of the 40th Annual ARCOM Conference,* 2-4 September 2024, London, UK, Association of Researchers in Construction Management, 809-818.

and (ii) lower risk of committing technical mistakes (Maia *et al.,* 2023), it is not sufficient to maintain the decarbonisation in the long run. This is due to dynamic building performance influenced by degradation and climate change (Darko *et al.,* 2023). Therefore, stepwise retrofitting, which refers to gradually implementing retrofit measures over multiple steps during an agreed period, can be utilised to maintain decarbonisation over the service life of a residential building (European Union 2019).

The Energy Performance of Buildings Directive (EPBD) in Europe initially recommended a 20-year timeframe for stepwise retrofitting implementation. Still, recent findings from the Intergovernmental Panel on Climate Change (IPCC) highlight the need for continuous retrofitting due to potential climate variations over the next century (IPCC 2023: 65; Magnan *et al.,* 2021). To cope with such climate variations and building degradation, Washington, DC enacted the Building Energy Performance Standards (BEPS) requiring continuous retrofitting every five years to achieve the prevailing Energy Star score (Department of Energy and Environment 2023). Yet, this approach is not applicable globally due to localised climate variations, diverse building characteristics, and varying rating systems (Luo and Oyedele, 2022). Therefore, a dynamic mechanism should be developed to determine the optimum timing between retrofitting steps. While Maia *et al.,* (2021) developed a techno-economic optimisation model to determine the optimal timing in the stepwise retrofitting process by maximising the net present value, it overlooks significant temporal variations, such as climate change, cleaner production, decarbonisation of the electricity grid, and embodied emissions. Furthermore, Bergfeld *et al.,* (2021) evaluated the emission reduction potential of periodical retrofitting every five years using a linear regression model, ignoring the temporal variations of many parameters. Moreover, considering social parameters is also crucial for long-term decarbonisation. The social dimension ensures a practical, acceptable, and sustainable retrofitting process for the occupants, further promoting their ongoing engagement in the long run (Jafar *et al.,* 2019). Yet, none of the existing models on stepwise retrofitting have considered this aspect. Therefore, this study aims to comprehensively investigate essential temporal parameters for timing stepwise retrofitting to maximise long-term emission reduction in residential buildings, promoting sustainable housing.

Stepwise retrofitting

While single step retrofitting significantly reduces emissions immediately, homeowners and landlords often prefer implementing fewer retrofit measures at a time (Energy Saving Trust 2011). Therefore, stepwise retrofitting becomes crucial to implementing a comprehensive set of retrofit measures over time (Liu *et al.,* 2021). Moreover, in stepwise retrofitting, financially capable households can initiate the procedure with deep retrofitting, maintaining decarbonisation through subsequent steps. Conversely, homeowners facing financial constraints can opt for shallow retrofitting steps, gradually achieving deep decarbonisation over a feasible timeframe.

In contrast to the single-step approach, stepwise retrofitting not only involves selecting retrofit measures but also considers additional aspects such as:

(i) Timing between subsequent retrofit steps: Determinants include technical requirements, climate change, household affordability, and social factors.

(ii) Retrofit packages in each retrofit step: Understanding the implementation of retrofit measures is crucial for assigning them into packages. This involves identifying potential combinations and dependencies between measures, to avert lock-in effects

(iii) Sequence of retrofit steps: Considering different principles is crucial to reduce lock-in effects in stepwise retrofitting, i.e. fabric first approach, which focuses on modifying the building envelope to reduce heating demand (Maia *et al.,* 2023). Conversely, if the building envelope is retrofitted shortly after replacing the heating system, the heating system may operate with excessive capacity for a period. Consequently, this lock-in effect persists until the next heating system replacement.

Researchers have primarily concentrated on the timing aspect of stepwise retrofitting, driven by its intricate complexity (Maia *et al.,* 2021; Maia *et al.,* 2023; Maia and Kranzl, 2019). Despite the potential benefits of stepwise retrofitting, researchers have made scant efforts to model this timing dimension, incorporating a set of parameters across different groups. For instance, Maia *et al.,* (2021) accounted for economic and technical parameters, whereas Bergfeld *et al.,* (2021) included environmental and economic parameters. However, none of the existing models on stepwise retrofitting have integrated social parameters. Yet, according to the UN Geneva Charter, the theoretical underpinning of sustainable housing comprises environmental conservation, economic efficiency, and social inclusivity and engagement (UNECE, 2015). Additionally, some social parameters could be identified from studies on trigger points. Trigger points are pivotal stages in a building's lifespan, providing less disruptive and more favourable circumstances for energy retrofitting. These trigger points may include social factors, such as heritage preservation or life events like marriage, moving into a new home, or retirement (Bui *et al.,* 2022; The Energy Saving Trust, 2011).

On the other hand, those parameters can be categorised as either static or temporal. Static parameters remain constant, while temporal ones change continuously. Temporal parameters, such as the energy efficiency of material production and the decarbonisation of the electricity grid, must be considered in modelling to ensure that the model outcomes align closely with real-world scenarios (Darko *et al.,* 2023). Nevertheless, existing models often overlook these factors, relying instead on static parameters (Bergfeld *et al.,* 2021; Maia *et al.,* 2021). For instance, Bergfeld *et al.,* (2021) assumed a constant emission rate in the energy over the study's reference period, regardless of the US government's policy trajectories for decarbonising the electricity grid. Furthermore, existing research on stepwise retrofitting has largely ignored the dynamic nature of climate in their models. However, the selected optimal combination of retrofit measures for a particular house evolves due to climate variations (Kang *et al.,* 2020). Thus, retrofitting done in the present may be insufficient for ensuring long-term energy efficiency. For instance, in Australia, most of the population resides in the temporal climate zone, where a notable increase in cooling demand is projected by the century's end, shifting these regions from heating-dominated to cooling-dominated (Barlow *et al.,* 2023). This underscores the importance of temporal parameters, particularly climate change, in modelling stepwise retrofitting.

METHOD

The research methodology is twofold: a desk study and expert interviews facilitating a comprehensive investigation. Existing literature provides limited case studies integrating temporal parameters to assess emission reductions in energy retrofitting for residential buildings, particularly lacking studies on stepwise retrofitting. Thus, a desk study was conducted to thoroughly examine the application of temporal parameters in energy retrofitting (Saunders *et al.,* 2019) before evaluating their relevance for stepwise retrofitting through interviews. Reliable secondary data availability provided additional justification for employing the desk study approach (Saunders *et al.,* 2019). Nine case studies were identified from selected articles to identify potential temporal parameters. Content analysis of desk study data enabled the identification of parameter frequency and essential parameters (Mayring, 2004).

The expert interviews involved nine professionals with over 15 years of experience in retrofitting and energy modelling (see Table 1). Expert opinions were crucial for validating parameters from energy retrofitting literature for stepwise retrofitting due to the differing temporal focuses of the two approaches. While energy retrofitting emphasizes short-term effects, stepwise retrofitting targets long-term impacts. Purposive and snowball sampling methods were used to select experts for semi-structured interviews. These interviews included both structured and unstructured questions. Each interview lasted for at least 45 minutes. Initially, experts were asked to discuss the significance of creating a detailed renovation roadmap, focusing on stepwise retrofitting. They were then prompted to discuss crucial perspectives or parameters for defining timing within the roadmap, actively seeking their input on social factors. Additionally, experts provided feedback on parameters from the desk study, capturing fresh insights at first and then validating desk study findings.

The consistency of data received among expert categories was evident, as the last interviewee in each category echoed the novel insights shared by their predecessors, indicating saturation in the sample. Thematic analysis of interview data was conducted with NVivo 14.23.1 software to derive themes and insights. Renowned for its flexibility and exploratory approach, thematic analysis allowed themes to emerge directly from the data, rather than relying on predefined categories (Grbich, 2013), facilitating the discovery of novel parameters.

Table 1: The profile of interviewees

Expert category	Designation and Experience	Anonymous Code
Academia	Professor (31 years); Senior Lecturer (16 years); Adjunct Professor (30 years)	I02, I06, I09
Industry	Director, Builder, and Energy Rater (22 years); Executive Chairman (35 years); Director and Builder (30 years)	I01, I04, I05
Policy	Senior Policy Officer (34 years); Sustainability Consultant (16 years); Policy Officer (27 years)	I03, I07, I08

FINDINGS AND DISCUSSION

Stepwise retrofitting lacks a universally agreed-upon sequence or standardised designs, installations, and technology configurations, posing challenges due to its multiple aspects. Moreover, focusing solely on one aspect can compromise the overall system performance. Hence, essential parameters for stepwise retrofitting were identified to promote sustainable housing (refer to Table 2).

Technical Parameters (TP)

TPs play a crucial role in delineating the temporal variations of emission data and serve as essential trigger points. In total, five TPs were identified through the desk study. Experts agreed on all five parameters for stepwise retrofitting and proposed two new parameters, TP05 and TP06, due to the long-term focus of stepwise retrofitting.

Table 2: Essential parameters of stepwise retrofitting

Code	Parameters	Sources	
		References	Interviews
	Technical Parameters (TPs)	[1], [2], [3], [4]	I01, I03, I07
TP01	The technical lifetime of retrofit measures [Number of Years]	[1], [2], [3]	I02, I03, I07
TP02	Emission decreases in the production process (cleaner production) [%/ Year]*	[1] – [9]	I02, I07
TP03	Thermal conductivity [u-value]	[2], [5]	I08, I09
TP04	Materials degradation [%/ Year]	-	I01, I06
TP05	Unexpected damages [probability (%)]*	-	I01, I06
TP06	Restumping [Frequency (f)]*	[1] – [9]	I02, I07
TP07	HVAC system details: type [categorical], efficiency [%], thermostat [°C]	[1] – [9]	I02, I07
	Environmental Parameters (EPs)	[1] – [9]	I01, I02, I04, I05, I07
EP01	Embodied emissions of retrofit measures [kgCO2eq./ Year]*	[2], [6]	I01, I05
EP02	Indoor ventilation rate [Air Changes per Hour (ACH)]	[2], [5], [6]	I06, I07
EP03	Local weather data {outdoor temperature [°C], solar radiation [W/m2], hours of sunlight [h], humidity [%], wind speed [m/s]}	[2], [3], [6]	I02, I05, I06
EP04	Emissions per kWh in the energy mix [kgCO2eq./ kWh/ Year]*	[2], [3], [6]	I02, I05, I06
	Economic Parameters (ECPs)	[10] - [12]	I01, I02, I03, I04, I06, I07
ECP01	Cost of retrofit measures (investment) [$]	[10] - [12]	I03, I08
ECP02	Labour cost [$/ hour]	-	I03, I08
ECP03	Minimum call-out fee [$]*	[10] - [12]	I01, I02, I05, I07
ECP04	Budget of the homeowner [$/ Year]	-	I02, I08
ECP05	Market value [$]*	-	I01, I06
ECP06	Rebates/ incentives/ government subsidies [$]*	[10] - [12]	I01, I06
ECP07	Green loans [$]	-	I04, I09
ECP08	Taxes/ initiatives/ credits related to carbon reduction [$] *	[10] - [13]	I04, I09
ECP09	Energy rate [$/ kWh]	[10] - [12]	I04, I09
ECP10	Annual operation and maintenance cost [$/Year]	[10] - [12]	I04, I09
	Social Parameters (SPs)	-	I06
SP01	Willingness of homeowners [x∈0,1] *	[14]	I01, I03
SP02	Point of sale/ rental/ refurbishment [Frequency (f)] *	[15], [16]	I08
SP03	Retirement*	[15], [16]	I02
SP04	Marriage*	[15], [16]	I02

Note: The asterisk sign (*) represents the parameters which have not yet been integrated into modelling stepwise retrofitting.

Unforeseen damages (TP05) can act as trigger points so any retrofitting model should have the flexibility to exploit such incidents through real-time data. For instance, experts from the industry highlighted that broken windows and rotten weatherboards could be leveraged to incorporate window upgrades and wall insulation. Restumping (TP06) is a process involving the replacement of wooden stumps to elevate a house. As I01 emphasized, "A lot of the old homes will need restumping, well, that's the time to get under there and insulate as well".

Technical Parameters (TP)

Therefore, TP06 was identified as an essential phenomenon in most old houses, especially in Australia and thus, it can act as a trigger point, influencing decisions on floor insulation. While previous research has employed expert feedback (Negishi *et al.,* 2019; Van de Moortel *et al.,* 2022) or historical data analysis (G ̈oswein *et al.,* 2021) to define the temporal variations of TP02, I07 and I09 underscored the necessity of integrating both approaches to mitigate the limitations inherent in each method individually. While experts unanimously agreed on the significance of TP03 in estimating HVAC demand, none of the existing studies, even those focusing on retrofitting, have investigated its temporal variations. However, TP04 aids in understanding the temporal variations of TP03, enhancing its accurate utilisation. The previous studies identified TP07 as a static parameter, overlooking factors like degradation and changes in occupancy.

Furthermore, experts highlighted the applicability of all TPs globally except restumping which is particularly applicable to a few countries such as the UK and Australia because of the similar nature of the old housing stock.

Environmental Parameters (EP)

The environmental category represents the essential parameters for assessing the long-term emission savings of stepwise retrofitting. The desk study identified five EPs in total. However, I06 and I09 pointed out that indoor temperature is irrelevant for assessing emission reductions, emphasising its significance only for thermal comfort analysis. Moreover, experts from all three categories emphasize the importance of considering both embodied (EP01) and operational emissions together to avoid overcompensating for embodied emissions while striving to reduce operational emissions. However, few experts had counterarguments about embodied emissions, for instance, I03 highlighted, " It's kind of modest on the overall scale. It's far from the most important thing". While some research on retrofitting has explored temporal variations of embodied emissions (EP01), studies concentrating on stepwise retrofitting have yet to address this aspect.

All three groups of experts unanimously agreed upon strategies to reduce embodied emissions, including (i) selecting materials with low carbon content (i.e. dense fibreglass over rock wool and bamboo for flooring), (ii) minimising high-emission materials (i.e. choosing the 30% to 60% cement replacement in the concrete), (iii) reusing materials (i.e. cleaning down and reuse bricks in old houses again), (iv) opting for recycled (i.e. recycled bricks and timber) and durable (i.e. using polished concrete floors for walkways and living spaces rather than carpets) options, and (v) prioritising regenerative sources (i.e. hemp and timber). These strategies sequentially align with the application of circular principles in energy retrofitting such as rethinking, reducing, reusing, recycling, and regenerating.

Concerning EP03, seven experts out of nine emphasized the importance of factoring in climate change when determining the timing of stepwise retrofitting. I08 further elaborated, " Even those net-zero houses we're building today might need some adjustments down the line to keep emissions low to adapt to climate change". On the other hand, EP04 is defined based on different policy scenarios for reducing emissions in each country. In Australia, EP04 can be delineated based on four emission trajectory scenarios, including ambitious global action, medium global action, core policy, and high price with the high price scenario representing the most aggressive decarbonisation trajectory and core policy scenario representing the most potential trajectory (ROAM Consulting 2011). Furthermore, experts highlighted the applicability of all EPs globally.

Economic Parameters (ECP)

ECPs play a crucial role in assessing the affordability of homeowners and serve as essential trigger points. Given that previous studies have assessed ECPs related to stepwise retrofitting, the initial literature review on this topic aided in identifying some of the ECPs listed in Table 2. Altogether, six ECPs were discovered from the secondary data. Experts confirmed that all six parameters are suitable for stepwise retrofitting and suggested four new parameters, ECP03, ECP05, ECP06 and ECP08.

Among them, ECP06 and ECP08 trigger the implementation of specific retrofit measures. ECP06 denotes financial incentives offered by governments or other entities to promote retrofitting. ECP08 refers to various fiscal measures to discourage emission-intensive activities and appliances, such as gas heaters. Minimum call-out fee (ECP03) stands for preventing losses for service providers/ tradespeople. I03 further emphasized ECP03, " So, you know, labour costs are very high in Australia: there's a minimum call-out Fee; you might need several different trades to be present in your home over a renovation process to undertake certain activities, you may need a builder, a carpenter, a plumber, a gas fitter, an electrician". Since multiple retrofit steps may necessitate each tradesperson's presence multiple times, retrofit packages should aim to reduce repeated callouts for the same trade. Retrofitting models have generally overlooked the market value increments (ECP05), despite being a significant consideration for house owners. For instance, households commonly choose visible features like solar panels, solar hot water systems, batteries, and rainwater tanks because demonstrating the value of less visible improvements like underfloor or wall insulation during rental or sale can be challenging.

ECP01 acts as an essential trigger point for stepwise retrofitting. Various strategies proposed by experts to reduce ECP01 include regulation for mass production of materials and implementing a package approach to facilitate scaling up retrofits across similar buildings or climate zones. For instance, the rapid adoption of double-glazed uPVC units in Western Europe, as noted by I02, can be attributed to mass production, resulting in decreased costs. Thus, the relationship between mass production and widespread adoption is bidirectional and dynamic. Balancing these variables in the macro economy decreases cost and increases retrofit measure adoption.

All ECPs undergo temporal changes, primarily driven by inflation and other specific factors. Additionally, experts noted the global applicability of all ECPs, although ECP03 may be restricted to certain countries due to their labor market characteristics.

Social Parameters (SP)

Social parameters serve as crucial trigger points for retrofitting, extending beyond simple energy-saving objectives. Some SPs were identified by investigating trigger points in the initial literature search before discussing them with experts. In total, four parameters were identified from the literature review. However, experts combined "moving into a new home" with SP02, while introducing a novel parameter, SP01. SP01 indicates the readiness of homeowners to undertake each retrofit step and can be represented as a Boolean value. SP01 depends on desire, need, and aspiration, which vary significantly among households. As suggested by I02, to encourage the "true" value for SP01, the retrofitting plan should align with the homeowners' preferred Home Improvement Plan (HIP). I05 emphasized, "You can't impose a retrofitting plan on people; it needs to be collaboratively developed with the homeowner."

Several experts (I01, I02, and I09) recommend encouraging deep retrofitting during property transitions to expand its implementation (see SP02 in Table 2). I07 made a counterargument, which suggests that retrofitting should not coincide with property transitions due to the significant capital investment required for home purchases. Still, other experts argue that deep retrofitting can increase the property's market value, thus weakening the strength of the counterargument. Therefore, given the focus of this study on individual owner-occupied single detached houses, the property transition period can be seen as a retrofit cycle during which multiple retrofit steps can be taken. This approach facilitates deep decarbonisation by the time of sale, further increasing the market value. In Australia, property sales occur approximately every 7 to 8 years, while rental turnovers happen every 2 to 3 years. Furthermore, as individuals' circumstances change, such as with family expansion, there will be additional space requirements. This also presents an opportunity to incorporate energy retrofitting.

As per I09, SP04 functions as a social trigger point, but economic considerations sometimes yield the opposite effect, making SP03 a more compelling opportunity than SP04. Furthermore, individuals often have more time to dedicate to home interventions during retirement (SP03). Additionally, experts noted the global applicability of all SPs, although SP02 may be restricted to certain countries based on the volatility of their real estate markets.

CONCLUSIONS

The research marks the first comprehensive exploration of essential temporal parameters for stepwise retrofitting. The findings revealed social dimension must be incorporated alongside technical, environmental, and economic aspects. This ensures that retrofitting processes are practical, acceptable, and sustainable for occupants, further fostering their continued engagement for sustained emission reduction in the long term. The determined novel parameters include across all four groups: (i) TPs (unexpected damages, restumping), (ii) EPs (temporal variations of embodied and operational emissions), (iii) ECPs (minimum call-out fee, market value, rebates/ incentives/ government subsidies, taxes/ initiatives/ credits related to carbon reduction), (iv) SPs (point of sale/rental/refurbishment, homeowner willingness).

Overall, the study contributes to knowledge by introducing new parameters for stepwise retrofitting. Additionally, it provides insights for practitioners, who can employ these parameters to achieve long-term emission reductions through stepwise retrofitting. Still, these parameters should be validated in real-case studies before application. Also, the identified parameters are tailored for individual buildings, primarily focusing on owner-occupied single-detached houses. As this research is ongoing, the next steps involve developing a comprehensive dynamic model using these parameters to estimate the optimal timing between steps for maximising long-term emission reduction, and case study application.

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