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Sustainable water management in construction: life-cycle embodied water assessment of residential buildings

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Abstract

Purpose – This study aims to enhance our understanding of sustainable water management in construction through a life-cycle embodied water assessment of a villa in the United Arab Emirates (UAE). It provides insights and recommendations for improving the water efficiency by identifying areas for potential embodied water saving and reduction in environmental impacts in the construction industry.

Design/methodology/approach – This study uses a life-cycle assessment (LCA) approach and focuses on a UAE villa as a case study. It analyses the embodied water consumption during construction (initial embodied water) and maintenance (recurrent embodied water) using an input–output-based hybrid analysis. Additionally, it compares the embodied water observations with the operational water usage and comprehensively evaluates the water consumption in the villa's life-cycle.

Findings – The initial (28%) and recurrent embodied water (42%) represent significant proportions of a building's life-cycle water demand. The structural elements, predominantly concrete and steel, contribute 40% of the initial embodied water consumption. This emphasises the importance of minimising the water usage in these materials. Similarly, internal finishes account for 47% of the recurrent embodied water. This emphasises the importance of evaluating the material service life.

Practical implications – These findings indicate the efficacy of using durable materials with low embodiment and water-efficient construction methods. Additionally, collaborative research between academia, industry, and the government is recommended in conjunction with advocating for policies promoting low embodied-water materials and transparency in the construction sector through embodied water footprint reporting.

Originality/value – Previous studies focused on the operational water and marginally addressed the initial embodied water. Meanwhile, this study highlights the significance of the initial and recurrent embodied water

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in the life-cycle water demand. It emphasises on the need for adaptable buildings with reduced embodied water and more durable materials to minimise the requirement for frequent material replacements.
Keywords Construction, Embodied water, Materials, Residential buildings, Service life
Paper type Research paper

1. Introduction

The availability of fresh water is rapidly becoming a severe concern worldwide. The United Arab Emirates (UAE) is among the driest regions with a limited freshwater availability (Saif *et al.*, 2014). According to the Intergovernmental Panel on Climate Change (IPCC), climate change is likely to result in further shortages of freshwater in this region (IPCC, 2022). Unlike the per capita global average of 180 L/day, the water consumption in the Gulf Cooperation Council (GCC) countries is estimated to be 560 L/day. Here, the consumption in the UAE is the highest (Qureshi, 2020). Seawater desalination is the predominant source of potable water (92%) in UAE's domestic and industrial sectors. Other unconventional sources of water such as wastewater reuse and the import of "virtual" water via goods from other parts of the world also help sustain the high-water demand. The UAE Water Security Strategy 2036 aims to reduce the total water demand by 21%. This requires increased efficiency of water use across all sectors (Ministry of Energy and Infrastructure, 2021).

Buildings have significant demands for various natural resources including water (Crawford and Pullen, 2011). To reduce the demand for water in various sectors, it is important to identify methods to reduce the water consumption during the construction and operation of buildings. Over 16% of the global water use is estimated to be linked to construction activities (Dixit *et al.*, 2022). The life-cycle water consumption of buildings accounts for 30% of the world's water usage. The reduction in water use for building operations has been the focus of efforts by governments and professionals. However, negligible attention has been paid to reducing the amount of water embodied in building construction (Stephan and Crawford, 2014). Our decisions with regard to the selection of construction systems and building materials can result in a severe strain on water availability. Therefore, this study conducts an embodied water analysis to contribute to the body of knowledge on sustainable water management in the construction industry by achieving the following objectives:

(1) Evaluate the total embodied water consumed throughout the life-cycle of a villa in UAE.

(2) Identify the building materials and components with the highest embodied water intensity. This would enable the prioritisation of areas for potential water-use reduction.

(3) Provide insightful recommendations for enhancing the water efficiency in the construction industry by identifying opportunities for embodied water saving and for minimising the environmental impacts.

2. Water consumption in buildings

Buildings consume large amounts of water during their various life stages. In the context of water shortage, it is imperative to reduce the water consumption by buildings. Wu *et al.* (2020) introduced a strategic framework based on green building tools to identify water-saving measures during the different phases of a construction project. It includes rainwater harvesting, recycled water use, water-saving technologies, devices, efficiency, monitoring of major water uses, leak detection, and continuous water monitoring. Another study evaluated São Paulo's water programmes. It demonstrated that economic incentives can help reduce water consumption (De Sousa and Fouto, 2019). The water consumption in buildings can be categorised into operational and embodied water.

Operational water: It is the water used during the operational phase of a building for daily activities (Stephan and Crawford, 2014). The operational water consumption in buildings is directly experienced and visible to the building occupants and managers, thereby generating immediate attention. Consequently, there has been higher awareness and focus on monitoring and reducing operational water consumption. This has resulted in more extensive research in this area. In many parts of the world, established benchmarks, standards, and regulations have been implemented to govern the operational water consumption in buildings. Operational water consumption is generally more convenient to access and quantify. This is because it can be monitored directly using metres and utility bills. These factors have motivated researchers to evaluate operational water management systems. This has resulted in an increase in literature on operational water consumption.

Embodied water: The water required for constructing and maintaining buildings, including the water used for manufacturing and transporting materials, is known as embodied water. Depending on the function of the process, it involves direct or indirect water consumption. (Crawford and Pullen, 2011). Direct water refers to the water consumed directly in the generation of the main product being analysed. Meanwhile, indirect water is the amount of water consumed in the upstream activities necessary for producing and providing the materials or components constituting the main product. A study by Dixit *et al.* (2022) on the embodied water assessment of different higher education buildings revealed that the indirect water consumption associated with materials, systems, and services is significantly higher (66–78%) than the direct water consumption associated with construction, installation, and administration processes (22–34%).

Embodied water can be categorised into initial and recurrent embodied water. The initial embodied water is typically associated with the upfront construction or production phase (Crawford and Pullen, 2011). In contrast, recurrent embodied water refers to the water consumed throughout the use phase of a building or product. It includes the water required for regular maintenance, repairs, renovations, and replacement of materials, components, or systems within the building or product (Stephan and Crawford, 2014). Understanding the significance of both initial and recurrent embodied water is essential for effective water management and reduction efforts in the building industry. By considering the entire life-cycle, including both the upfront and ongoing water requirements, stakeholders can make informed decisions to minimise the overall water footprint and promote more sustainable and water-efficient solutions (Dixit *et al.*, 2022).

2.1 Effect of building materials on building's embodied water

Water is an essential natural resource for producing building materials. With the increasing concern regarding the depletion of freshwater resources owing to the growing population, urbanisation, climate change, and other factors, the study of water consumption associated with different building materials has become important.

A 2004 Australian study determined the embodied water consumption by residential buildings to be 33.2 kL/m^2 (Treloar and Crawford, 2004). Another study on 17 non-residential buildings in Australia reported a maximum embodied water consumption of 20.1 kL/m^2 (McCormack *et al.*, 2007). It revealed that the water consumption during construction varies among different building types. The selection of building materials directly impacts the embodied water consumption of buildings and other assets in the built environment. The amount of water required for building materials depends on several factors including the material properties, raw materials, processing, and manufacturing processes (Crawford *et al.*, 2022). Materials that undergo significant processing typically require more water. For example, the production of cement, concrete, steel, and aluminium requires significant processing, and these are considered water-intensive materials (Wärmark, 2015). A study in China indicated that urban residential buildings exhibited a water footprint 55–130% higher than that of rural buildings. This observation indicates that urban construction practices rely more significantly on processed building materials such as steel and concrete, compared with rural areas, where buildings make higher use of natural and less processed materials (Chang *et al.*, 2016). Another study from Iran computed the water consumption associated with the construction of residential buildings as 20.8 kL/m2, with 58% attributed to steel (Heravi and Abdolvand, 2019). Supply chain factors including the resource availability and transportation distance significantly affect the embodied water in buildings (Hoekstra, 2017).

The embodied water consumption in construction can be reduced by substituting high-embodied water materials with lower-footprint alternatives and optimising the building design for efficient space and material use (Dixit *et al.*, 2022). Embodied water assessment studies are significant because of their contribution to addressing water scarcity concerns and environmental sustainability. However, globally, the understanding of construction embodied-water remains limited because of the insufficient research conducted in diverse contexts (Sharma and Chani, 2022). Further research can provide insights into the environmental impact, resource consumption, and strategies for mitigating its impact. Evaluating various contexts helps identify region-specific challenges and opportunities related to the embodied water in construction. An expanded research agenda could advance sustainability goals and promote responsible water-management practices in the construction industry.

2.2 Embodied water assessment

The embodied-water analysis methods can be broadly categorised into process analysis, input–output (I-O) analysis, and hybrid analysis (Dixit *et al.*, 2022; Stephan and Crawford, 2014).

Process analysis is a widely used method to assess embodied energy and embodied water, and to evaluate the environmental impact of product manufacturing (Rauf *et al.*, 2022a). In this method, data from various processes, products, locations, and environmental flows are gathered for assessment (Treloar, 1997). Owing to the inherent challenges in obtaining complete manufacturer data, which are generally characterised by incomplete information, the system boundary for this approach may be susceptible to incompleteness (Rauf *et al.*, 2022b).

An input–output analysis traces and quantifies the water required to manufacture a product using economic data. The inter-industry transactions (input–output tables) are used to define the resource flows. Process-based approaches consistently produce lower values than input–output methods. Although this approach provides systemic completeness by identifying the energy flows throughout the supply chain in an economy, it combines dissimilar products and results in a procedural black box within individual economic sectors (Baird *et al.*, 1997; Rauf, 2022). Additionally, calculation errors may occur from the variations in product price estimations or assumptions, handling of economic data, and potential multiple or double counting of resources (Dixit, 2017).

In hybrid analysis, the process and input–output analysis methods are combined (Crawford *et al.*, 2015). This method eliminates the truncation errors associated with process analysis and more accurately assesses the environmental impacts associated with buildings (Hong *et al.*, 2016). Two types of hybrid analyses are available: process and input-output-based. In a process-based hybrid analysis, the embodied energy and water are calculated by quantifying individual products that are provided, and multiplied by extrapolated intensities obtained from the input–output analysis (Crawford, 2004; Treloar, 1997). For each material, the process data results of the water required to produce it are added to "the difference between the total water intensity of the input–output path of the basic material. Then, it is multiplied by the total price of the basic material" (Crawford, 2004). Process-based hybrid analysis involves incomplete system boundaries. Meanwhile, input–output-based hybrid analysis tends to address this limitation, which makes it more reliable (Rauf *et al.*, 2021).

Therefore, an input–output-based hybrid analysis was employed to calculate the embodied water in this study.

3. Research methodology

To achieve the aim of this study, a methodology based on the life-cycle assessment (LCA) approach was used. A villa in the UAE was used as a case study. LCA involves distinct phases (goal and scope definition, inventory analysis, impact assessment, and interpretation) as defined by ISO 14040 (2006) and ISO 14044 (2006). These stages provide a systematic and structured approach for conducting an LCA study and are used as a framework for conducting the proposed research activities (see Figure 1).

3.1 LCA stages

3.1.1 Goal and scope. In this phase, the purpose of an LCA is defined, and the environmental flows for this study are selected. Environmental flows can be defined as a comprehensive evaluation of the resource inputs (including water, energy, and raw materials) and concurrent outputs (such as waste, greenhouse gases, and pollutants) at each stage of a built asset's life-cycle.

The identification of the study's limitations or system boundaries is another important aspect that can influence the comprehensiveness, accuracy, and relevance of the results. The system boundary for this study considered the water consumption across different life-cycle stages of the case-study building, including that for raw material extraction, processing, transportation, manufacturing, construction, and maintenance. The end-of-life stage (demolition and disposal) was not considered in this study because of the significant uncertainty (Stephan and Crawford, 2014) regarding the future status and water implications of long-lasting building materials beyond their useful lifespans, including their potential recycling and reuse processes. This study was limited to the life-cycle embodied water assessment of the substructures and superstructures, external and internal walls, finishes,

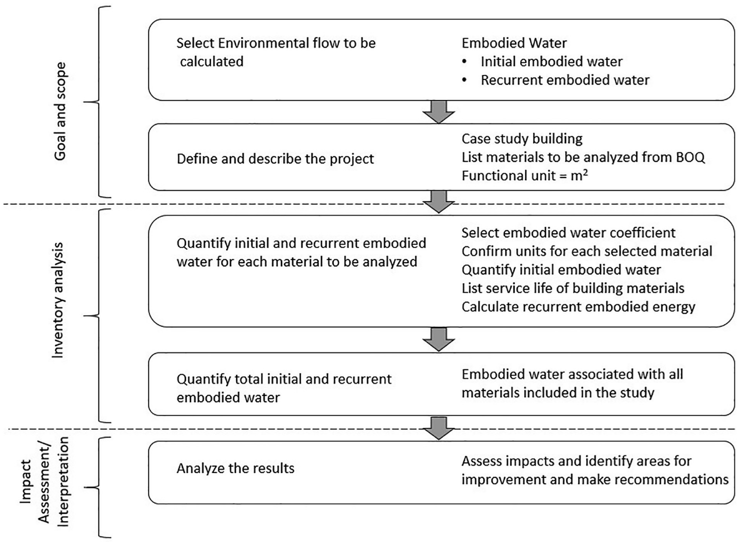

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Figure 1. Methodology framework based on ISO 14044 (2006)

windows, and other components such as joinery and ironmongery work. The embodied water associated with landscaping, furnishing, electrical, plumbing, and HVAC systems was excluded from the analysis. This omission was necessitated by the unavailability of pertinent data and the need to maintain a manageable scope to ensure a focused and feasible study.

Case study building: Villas are among the most prevalent types of residential properties in the UAE. These spacious houses are preferred by typical Emirati families and are available in various configurations ranging from 3 to 10 bedrooms (Giusti and Almoosawi, 2017). For our case study, we selected a detached villa in Al Ain, UAE. Al Ain experiences lengthy, scorching, dry summers, whereas the winters are short, pleasant, dry, and mostly clear (Haggag *et al.*, 2017).

The two-story villa has an area of 532 m^2 (Figure 2). It was constructed using reinforced-concrete structural elements (footings, columns, beams, and floor slabs), with a total of 451 m^3 of concrete utilised in its construction. The external walls were constructed with 20 cm concrete hollow blocks with insulation, cement plaster, and paint, and feature artificial stone cladding in certain areas. The internal walls were constructed using concrete blocks, cement plaster, paint, and cladding, with marble and ceramic tiles in certain areas. Depending on the usage of the space, concrete floors have marble, granite, and ceramic tile finishes. Double-glazed aluminium-framed windows and teak-framed doors are used. Refer to Table 3 for a comprehensive list of the materials included in this study.

3.1.2 Inventory analysis. Life-cycle inventory analysis involved the calculation of the water embodied in the construction and maintenance of the case study building over its average building service life. In this study, a building service life of 50 years was applied. It is the most commonly observed service life of residential buildings in previous studies (Crawford *et al.*, 2010; Mackley, 1998; Ortiz *et al.*, 2009). To calculate the initial embodied water of the case-study villa, the quantities of materials from the bill of quantities were multiplied by the wastage factor of each material to account for over-ordering and on-site wastage. The amount of embodied water provided to each material was quantified. An input–output-based hybrid analysis approach was used to calculate the embodied water. The embodied water coefficients for each

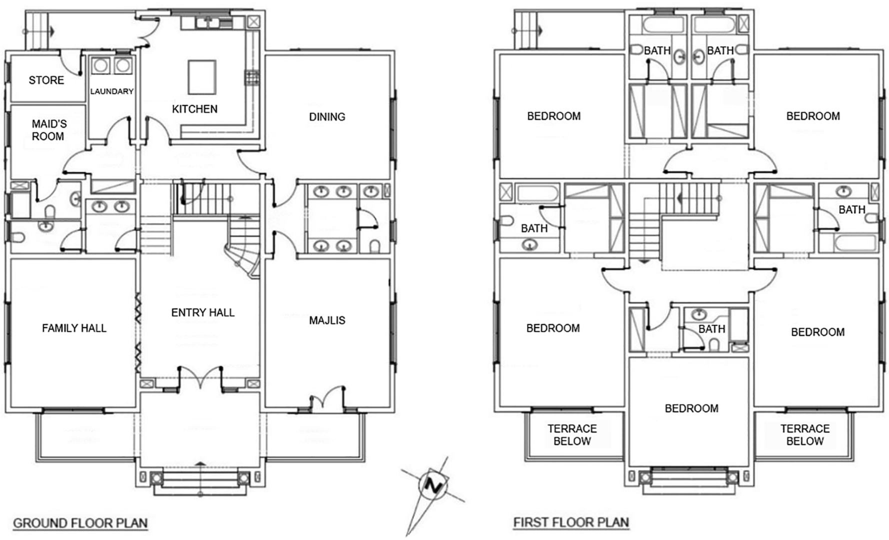

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Figure 2.
Ground and first floor plan of the case study villa

material from the EPIC database (Crawford *et al.*, 2019) were multiplied by the provided quantities to calculate the embodied water. An Excel spreadsheet was used to assist this process. It facilitated precise calculations and a thorough data analysis (see Figure 3). The embodied water in the building was calculated by adding the embodied water associated with each material included in this study. However, this process-based hybrid analysis approach underestimated the values because of the truncation errors in the process data (Lenzen and Crawford, 2009; Lenzen and Dey, 2000). To complete the system boundary, the water associated with nonmaterial inputs (i.e. water encompassing the on-site construction process, transportation of materials to the site, and provision of financial and related support for the construction process (referred to as the remainder)) was added to this initial value. The remainder was calculated by applying a disaggregated energy-based input–output model. The recurrent embodied water was calculated by the approach used to quantify the initial embodied water. The average service lives of different construction materials from the available literature were used for this purpose. Table 1 lists the service lives of the selected materials. The water embodied in each replaced material was multiplied by the number of replacements of that material over the building's lifespan. The total recurrent embodied water for the house was the sum of these values. To accurately calculate the number of replacements for each material, the service life of the house was divided by the average service life of the material. We subtracted one to account for the material used in the initial construction. This value was rounded off to the nearest whole number considering that materials can only be replaced in whole numbers. The life-cycle embodied water was determined by adding the initial and recurrent embodied water.

3.1.2.1 Calculating life-cycle operational water. Although this study primarily examined the life-cycle embodied water of the villa throughout its life span, a comparison with the

Item		Unit	Qty	Wastage Factor	Delivered quantity	Emobodied water (L/unit)	Emobodied water (PBHA)-(Litre)
SUPERSTRUCTURE WORK							
3.10	Columns	M3	21	1.15	24.15	4355.00	105173.25
3.11	Beams	M3	26	1.15	29.9	4355.00	130214.50
3.12	Solid Slabs 25 cm thick	M3	112	1.15	128.8	4355.00	560924.00
3.13	Solid Slabs 18 cm thick	M3	5	1.15	5.75	4355.00	25041.25
3.14	Parapet	M3	30	1.15	34.5	4355.00	150247.50

Source(s): Figure by authors

Figure 3. Screenshot of the Microsoft Excel sheet used for calculating embodied water

Material	Material service life (years)
Concrete	Life time
Concrete blocks	Life time
Insulation	Life time
Plaster – cement based	15
Paint—exterior	7
Paint—interior	7
Artificial stone cladding – exterior	15
Tiles ceramic – walls	13
Tiles ceramic – floor	10
Tiles granite – Floor	10
Tiles marble – Floor	10

Source(s): Table by authors

Table 1. Material service life values of selected building materials used in the study

life-cycle operational water was also conducted to demonstrate its relative significance. Monthly water bills containing water consumption data for similarly sized villas over the past three years were used to calculate the operational water consumption. The water usage data from these bills were extracted and consolidated to ensure consistency of units (litres). Subsequently, the total water consumption over these three years was calculated by summing up the data for each month over the three-year period. The resulting operational water quantity was then divided by three to calculate the average annual water consumption. Daily water consumption for the seven-member household was calculated by dividing this annual water quantity by 365. To calculate the life-cycle operational water consumption, the average annual water quantity was multiplied by the service life of the building (50 years). It's important to note that this study solely examines operational water consumption within households, encompassing activities like drinking, cooking, bathing, and sanitation. This distinction is crucial as it differs from broader per capita water consumption statistics that include multiple sectors and activities beyond domestic use.

3.1.3 Impact assessment and interpretation. The final step was to analyse and interpret the embodied water results to identify the areas accounting for the high embodied water consumption. The results were discussed to make recommendations to reduce the water consumption during building construction. This phase involved considering the strengths and limitations of the analysis, identifying opportunities for improvement, and communicating the observations to stakeholders. Microsoft Excel graphs were used as visualisation tools to present the results, which rendered these more accessible and comprehensible to stakeholders and decision-makers.

3.2 Using EPiC database

A thorough and credible life-cycle embodied water assessment necessitates a robust database containing well-documented relative water intensities. The use of a local database for LCA enhances its accuracy, relevance, and specificity (Cirotha *et al.*, 2019; Ossés de Eicker *et al.*, 2010). The research on operational water is extensive in the UAE, whereas that on embodied water is limited. This is aggravated further by the absence of an embodied-water intensity database. In this situation, a non-local database can potentially provide effective data and information that can be used as a starting point for assessment. Although it may not capture the specific characteristics of the study area, it can provide general data on water consumption and embodied water intensities. An example is Latin America, where non-local LCI data are used owing to the deficiency of local LCI data (Ossés de Eicker *et al.*, 2010). Therefore, the EPiC database (Crawford *et al.*, 2022) was used to calculate the embodied water in the selected villa. The EPiC database has been applied successfully outside its original developmental context in Australia. This demonstrates its reliability in the absence of a localised database and its international adaptability. Table 2 shows the embodied water values sourced from EPiC database for the selected materials used in the case study building.

4. Results and discussion

4.1 Life-cycle embodied water

The results revealed that the embodied water associated with the selected case-study villa over 50 years was 26,829 kL. Considering the unit area, the embodied water amount was 50.43 kL/m^2. The initial embodied water of the selected case study villa was determined to be 10,818 kL. Meanwhile, the recurrent embodied water over the life of the building was determined to be 16,011 kL. Considering the unit area, the initial and recurrent embodied water were 20.33 kL/m^2 and 30.1 kL/m^2, respectively. Table 3 presents a breakdown of the initial, recurrent, and life-cycle embodied water values for different building assemblies and materials.

This significant amount of embodied water demonstrates the importance of analysing the embodied water associated with different parts of a building to identify the areas that accounts for most of the building's embodied water consumption.

Figure 4 shows a detailed breakdown of the life-cycle embodied water consumption for various components of the villa. Figure 5 shows the proportions of embodied water consumption for these building components. The embodied water associated with the construction of the structural elements of the substructures and superstructures (footings, columns, beams, and floor slabs) was observed to be the highest among all the building components (4,334 kJ). These structural elements mainly consist of concrete and steel, and represent 42% of the total initial embodied water consumption of the villa. This emphasises the potential for reducing the initial embodied water consumption related to the construction of these building assemblies. These structural elements do not require material replacement during the useful life of a building. Hence, the life-cycle embodied water for the structural components is equal to the initial requirements. From a life-cycle perspective, the internal finishes account for the highest embodied water consumption (9,607 kL). The internal finishes

Table 2. Embodied water values for selected materials sourced from EPiC database

Material	Unit	Embodied water (L)
Concrete 40 MPa	M3	4,355
Steel – reinforcement bars	KG	44.3
Concrete block	KG	3.7
Granite – dimension stone	KG	16.5
Ceramic tiles	KG	15.2
Paint – water based	KG	206
Paint – solvent based	KG	197
Glass	M2	251
Cold rolled steel	KG	77.6

Source(s): Table by authors, Crawford *et al.* (2022)

Table 3. Initial, recurrent and life-cycle embodied water consumption of selected components of the case study villa

	Initial embodied water	Recurrent embodied water Unit (KL)	Life cycle embodied water
Substructure work – concrete	1,141	0	1,141
Superstructure work – concrete	1,299	0	1,299
Substructure – steel	886	0	886
Superstructure – steel	1,008	0	1,008
Walls – blocks work (Solid Block @425 kg/m^2, Hollow Blocks @275 kg/m^2)	1,864	0	1,864
Internal finishes	2,105	7,502	9,607
Floor finishes- marble, granite, ceramic tiles	806	3,224	4,030
Skirting – marble, granite	306	1,224	1,530
Internal wall finishes – plaster, paint, ceramic tiles	774	2,337	3,111
Ceiling Finishes – plaster, gypsum board, paint	219	717	936
External finishes – Cement plaster, paint, artificial stone	335	1,012	1,347
Aluminium and glass work	786	3,133	3,917

Source(s): Table by authors

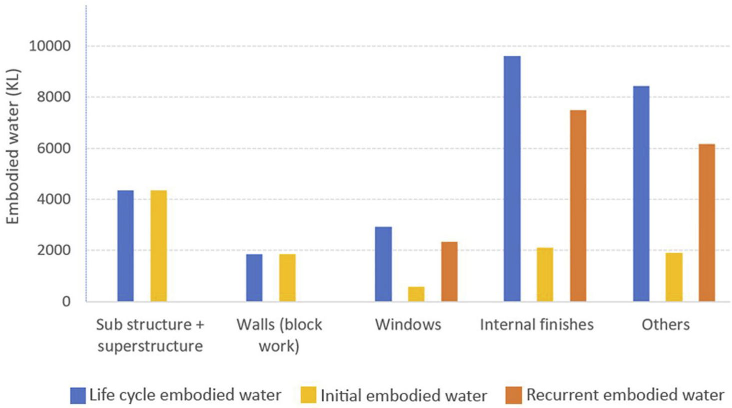

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Figure 4. Initial, recurrent, and life-cycle embodied water consumption of the case-study villa

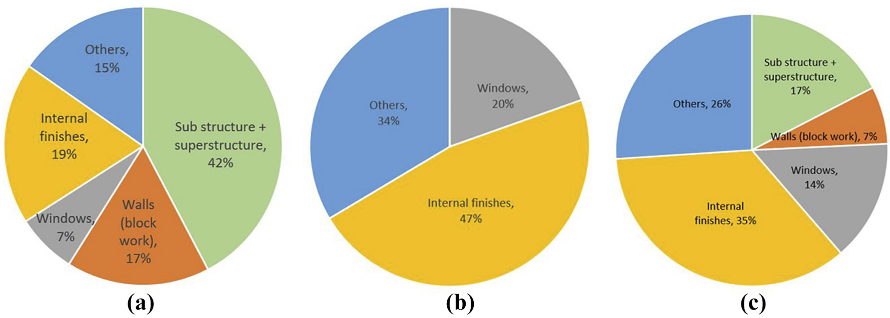

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Figure 5. Proportion of different building components for (a) initial (b) recurrent, and (c) life-cycle embodied water consumption

included in this study primarily consists of floor finishes (marble, granite, and ceramic tiles), wall finishes (plaster, paint, and ceramic tiles), and ceiling finishes (plaster, gypsum board, and paint). The initial embodied water associated with the internal finishes was 2,105 kL (19%). However, most of these finishes require material replacement every few years. Therefore, the associated recurrent embodied water is significant at 7,502 kL. This results in a high proportion (35%) of life-cycle embodied water consumption. The typical design of a villa also contributes to the high proportion of life-cycle embodied water. In the UAE, villas generally do not have an open living plan for cultural and social reasons, and are characterised by more internal walls and partitions. This results in a higher wall surface area required for the building materials and finishing. This indicates that the internal finishes present the highest potential for reducing the recurrent and life-cycle embodied water consumption.

The life-cycle embodied water values associated with walls, blockwork, and windows were determined to be 1,394 kL and 588 kL, respectively. These represent 7 and 14%, respectively, of the total embodied water consumption of the villa. The life-cycle embodied water associated with the other building components included in this study was determined to be 3,769 kL. The materials and components in this category primarily consist of wooden doors, cabinetry work for kitchens and bathrooms, as well as stainless-steel stair railings. This represents 26% of the total embodied water consumption of the villa.

This study demonstrated that concrete and steel present the highest potential for reducing the initial embodied water consumption. A significant amount of water is used to produce steel (44.3 L/kg) and concrete (4,355 L/m^3). Because both the materials are used in large quantities, one should utilise every opportunity available at the design and construction stage of a building that may help reduce the consumption of embodied water associated with these two materials. Efficient and optimised designs (such as reducing the thickness of a concrete slab without compromising its performance) can facilitate embodied water reduction efforts. Similarly, the reduction of waste at the construction stage also aids this aspect. Evaluating the feasibility of using alternative materials or material mixes with lower water footprint may yield a significant reduction in water consumption. Manufacturers can also play a role in improving the manufacturing processes with lower environmental impacts including the water consumption. This study revealed that in the attempts to reduce the life-cycle embodied water consumption, internal finishes emerge as the most potential area because of the large quantities of recurrent embodied water. To address this, measures such as selecting durable materials, promoting the use of recyclable materials, adopting efficient construction practices, and integrating LCA into design decisions can be implemented to reduce the water consumption associated with internal finishes.

4.2 Life-cycle operational water

Although this study primarily examined the life-cycle embodied water of the villa throughout its life span, a comparison with the life-cycle operational water was also conducted to demonstrate its relative significance. Monthly water bills over the past three years for similarly sized villas were used to calculate the operational water consumption. Drawing on data from water bills, the average daily water consumption for this seven-member household in the UAE was 630 litres. Life cycle water consumption over the 50-year lifespan, considering routine activities like bathing, cooking, washing, and cleaning, resulted in a total of 11,498 kilolitres. This accounts for 30% of the total water consumption over 50 years of the building life-cycle (Figure 6). Meanwhile, the life-cycle embodied water accounts for 70%

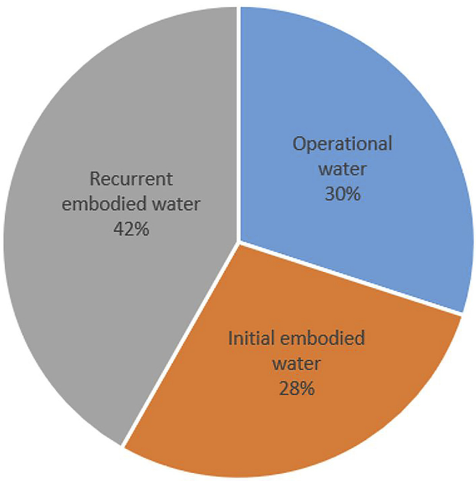

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Figure 6.
Proportion of life-cycle operational and embodied (initial and recurrent) water consumption for the case-study villa over its 50 years life-span

(28% initial and 42% recurrent embodied water). This indicates that although the operational water use is a significant factor, addressing embodied water (particularly the initial embodied water associated with structural elements and the recurrent portion linked with internal finishes) through measures such as material selection and efficient construction practices is important for holistic water reduction throughout a building's life-cycle. Regulatory bodies can play a pivotal role by developing and enforcing building codes and standards requiring water-efficient building materials, construction methods, and design practices. They can also promote transparency in disclosing embodied water information for building materials to facilitate informed decision-making in material selection.

5. Limitations

The primary focus of this study was the implications of embodied water in residential buildings in the UAE. Although it briefly acknowledges the connection to the operational water demand in the case-study villa, it is crucial to base all decisions aimed at reducing water demand on a comprehensive life-cycle approach that considers all the aspects of water consumption throughout a building's life-cycle. This approach is essential for preventing unintended shifts in water demand from one stage to another.

The use of the EPiC database (owing to the absence of a localised database for embodied water calculation in the case-study villa) is another limitation. This study presented a compelling case that validates the necessity of a context-specific database for embodied water analysis.

6. Conclusion

This study aimed to calculate the embodied water for a (case study) residential villa in the UAE to identify areas where water use can be reduced. Although the operational water usage is significant (30%), this study revealed that embodied water (both initial and recurrent) constitutes a substantial portion (70%) of the total water consumption in a building's life-cycle. This emphasises the need to address the water usage during the operational phase as well as the design, construction, and maintenance stages of a building's life-cycle to achieve more sustainable water management. Most previous studies omitted the role of recurrent water consumption. The results of this study revealed that a significant amount of embodied water is associated with buildings, representing 28 and 42% of the life-cycle water consumption over a 50 years lifespan. The structural building elements made mainly of concrete and steel were determined to account for 40% of the total initial embodied water consumption. This emphasises the importance of identifying methods to reduce the embodied water consumption associated with these building components and materials. Similarly, the internal finishes accounts for 47% of the recurrent embodied water. This emphasised the importance of material service-life considerations. Overall, this study verified the need to reduce the embodied water associated with the construction of buildings. It requires all the stakeholders in the industry to be engaged in such efforts. The substantial quantity of embodied water revealed by this analysis also emphasises the significance of analysing the specific components of buildings to identify the key contributors to the overall embodied water consumption. The significant share of recurrent embodied water in the life-cycle water demand emphasises the need to design adaptable buildings with durable materials that involve a reduced need for frequent renovations and material replacements. The findings from this study and similar research (Dixit *et al.*, 2022; Stephan and Crawford, 2014) can support efforts to identify areas for improved water management and thereby, enhance sustainability. This may involve recommending low embodied-water materials during design and adopting sustainable construction practices such as lean construction, prefabrication, and modular methods to minimise wastage. In addition, the utilisation of recycled and locally sourced materials with lower water content is crucial. Furthermore, conducting educational programs to enhance industry awareness and promote research partnerships between academia, industry, and government agencies could contribute significantly. Advocating policies that promote low embodied-water materials and enhance transparency in the construction sector by reporting embodied water footprints are also essential. When integrating low embodied-water materials into construction projects, assessing the embodied energy is essential to provide a more holistic view of the material's environmental impact.

Future research: This study demonstrated the significance of embodied water in residential villas in the UAE and emphasised the need for its extension to diverse building typologies in the region. To mitigate the environmental impacts related to water consumption, further investigation is required to develop and apply strategies to reduce both initial and recurring embodied water in construction. Further studies are required to assess the life-cycle embodied water of alternative materials and construction systems, investigate the influence of building service life and material selection on life-cycle embodied water under various scenarios, and investigate the potential for recycling to affect the embodied-water requirements of buildings. Furthermore, it is imperative to develop a localised database of embodied water pertaining to different materials. This necessitates future research.

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