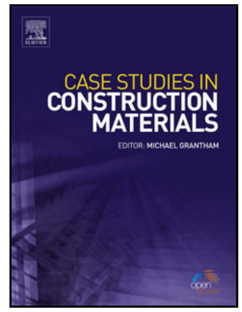



Title: Life cycle cost of different Walling material used for affordable housing in tropics.

Authors: Chameera Udawattha, Rangika Halwatura

PII: S2214-5095(16)30099-7
DOI: http://dx.doi.org/doi:10.1016/j.cscm.2017.04.005
Reference: CSCM 93

To appear in:

Received date: 10-11-2016
Accepted date: 12-4-2017

# Life cycle cost of different Walling material used for affordable housing in tropics.

Chameera Udawattha[1]* and Rangika Halwatura[2]

*Department of Civil Engineering, University of Moratuwa*

**Abstract**

The energy consumption of affordable housing industry plays a vital role in the environmental sustainability, waste generation and energy consumption. The development of sustainable housing construction methodology helps its country's economic development and sustainable development. Wall and roof are the most significant building component in a dwelling unit. The walling materials can determine the cost of the building as well as the total life cycle cost of a dwelling unit. In this study, the total life cycle cost of a basic dwelling unit in Sri Lanka, made of mostly available walling materials such as Brick, Hollow cement block, and Cabook, the Mud concrete blocks were calculated by using energy accounting hierarchical structure. The life cycle cost incurred due to change in above-mentioned walling materials were calculated and measured. Additionally, total LCC compared and analyzed.

The results show that mud concrete block is the most suitable walling material. The brick has the highest account for the embedded energy. The hollow cement block is the worse building materials in tropics and its carbon footprint is comparatively higher. Even though the brick has higher embedded energy and construction cost, in a long run brick is less expensive than hollow cement block and Cabook walling material. Concluding, mud concrete block is comparatively most sustainable walling material for building affordable housing in tropics.

***Keywords:*** *Tropical climate, Embodied Energy, Life cycle cost, walling materials, construction cost, maintenance cost and operation cost.*

---

*Chameera Udawattha
*Email address: 158042N@uom.lk* (udawatthe@gmail.com)
*Phone Number: +94777222658.*

# 1 INTRODUCTION

## Acronyms

| | |
|---|---|
| *BOQ* | Bills of quantities |
| *Cab* | Walling material made of hard soil cuts. |
| *CC* | Cleaning Cost |
| *EC* | Energy Cost |
| *EE* | Embedded energy |
| *FC* | Fixed Cost |
| *HCB* | Hollow cement Block |
| *IC* | Initial Cost |
| *LCC* | Life Cycle Cost |
| *M* | Medium scale Buildings |
| *MC* | Maintenance Cost |
| *MCB* | Mud concrete Block |
| *NPV* | Net present values |
| *NTA* | Not available |
| *OC* | Overheads |
| *Off* | Office Building |
| *Re* | Refurbishment |
| *Re* | Retrofit |
| *Res* | Residential Buildings |
| *RV* | Resale value |
| *SI* | Suitability Index |
| *UC* | Utilization Cost |

Selecting energy-efficient construction method or construction materials for affordable dwelling units have an effective impact on environment conservation(Adalberth 1997)(Gao et al. 2001)(Thormark 2002) because the quantities are higher comparing other building typologies, like offices warehouse etc.(Central Bank of Sri Lanka 2016). Calculating embedded energy and life cycle cost is in a way stepping towards the environmental conservation(Zabalza Bribián et al. 2009). Thence, this study endeavors to measure the environmental sustainability of the application of different walling materials.

## 1.1 The objective of this research

The objective of this research is to empathize the energy content of different walling materials used to build affordable houses in tropical climatic condition and compare their life cycle cost. Different types of walling materials were selected for the study considering their popularity. National statistical data was used to understand the most popular walling materials in the country.

In addition, newly invented walling materials such as mud concrete block (MCB) (Halwathura 2016) used to compare with existing walling material pallet.

Mud concrete block is a novel walling material. This is not the typical cement composed soil block. The mud concrete block is a walling block made of soil. In the composition of MCB, sand and metal of concrete are replaced by fine and coarse aggregates of soil. The precise gravel and sand combination governs the strength of the MCB. Cement in this soil concrete is also used as a stabilizer in very low quantities.

And also, this research may alleviate to constitute a concrete argument in selecting walling materials not only for the construction however, also for the total lifespan of affordable dwellings in the country.

Walling materials are important because it plays an immense role in the total cost of the building, life cycle cost, and energy content (see the Table 1). It accounts for more than 15% of the total cost of the building in Sri Lanka (Udawattha & Halwatura 2016b). Not only the cost but also, the roof and wall material is important in reducing the external heat gain, they are our third skin(Sartori & Hestnes 2007)(VARGHESE 2015)(Yang et al. 2014). Comparing different walling materials, however, also ranking those walling materials is the extended objective of this research. Then this study would help the funding agencies and general public to understand the real value when selecting walling materials for their affordable houses and choose on the best suitable material considering the embedded energy and total life cycle cost.

## 1.2 Recent attempts to compare different walling material's and their life cycle cost

There have been many attempts to calculate and compare LCC of different waling materials. However, there are few studies were done in tropical climatic conditions where the walling materials is very important to achieve the thermal comfort and reduce the LCC (Rohintan. Emmanuel 2004). And also most of these studies are based on general industry used walling materials such as Brick(Takano et al. 2015), wood cladding(Mithraratne & Vale 2004a) and steel envelop walling materials like steel cladding(Scheuer et al. 2003) etc. There only few studies (see the Table 1) were focused on affordable housing walling materials such as brick cement block Mud concrete block etc. Thence, this study is focused to calculate the LCC of walling materials used to build affordable houses in Sri Lanka.

The idea of affordability is the ability to purchase a particular item. The affordability index comes in housing sector where the median income family may be able to purchase particular house model in a country. If a particular house value is 100 affordability index is above 100 indicating that an item is less likely to be affordable and values below 100 indicating that an item is more affordable for a medium income house(Stone 2006). The affordable housing is well defined in the United Nations housing programme as well as Local government housing programme(Chen et al. 2010).

*Table 1: Recent attempts to calculate life cycle cost of different buildings and building materials*

| Source | Country | Nos. of cases | Type of building | Type of walling materials | Size ($m^2$) | Life-span |
|---|---|---|---|---|---|---|
| **Delbert** (Adalberth 1997) | Sweden | 1-2 | Res.m | Gypsum wall board | 700-1520 | 50 |
| **Atsushi Takano**(Takano et al. 2015) | Finland | 5 | Other | Brick ,Cement fiber board, Wood plank, Galvanized steel sheet | 120 | 50 |
| **Cole and Kenan** (Cole & Kernan 1996) | Canada | 14-25 | Office | Wood and steel frame | 4620 | 50 |
| **Crawford, Robert H**(Crawford 2011) | Australia | 1 | Res. | Bricks | 254.2 | 50 |
| **Dutil, Rousse, Daniel**(Dutil & Rousse 2012) | Canada | | | | | |
| **Emmanuel** (Rohintan. Emmanuel 2004) | Sri Lanka | 4 | wall | Brick, Cement blocks, Wattle, and daub | $10m^2$ | 60 |
| **Fay et al.** (Fay et al. 2000) | Australia | 26–27 | Res | | 128 | 50 |
| **Feist** (Feist 1997) | Germany | 28–33 | Res | gypsum plaster covering all internal surfaces; woodchip wallpaper, water paint | 156 | 80 |
| **Hallquist** | Norway | – | Res m | | ? | 40 |
| **Hamidul Islam D**(Hamidul Islam D 2012) | Australia | 3 | Res. | FC Sheet, Building paper (reflective foil) Insulation and Air gap Softwood plates, studs, noggins Plasterboard | 101 | 50 |
| **Keoleian, Gregory a Blanchard, Steven Reppe, Peter**(Keoleian et al. 2001) | USA | 2 (re) | Res. | Brick | 228 m2 | 50 |
| **Li, Zhuguo**(Li 2006) | Japan | 3 | store | Steel structure, steel cladding | 15000<br>2000<br>1800 | -- |
| **Mithraratne and Vale** (Mithraratne & Vale 2004b) | New Zealand | 36–38 | Res | Timber studs and wall framing, plaster board, insulation, skirting, brickwork, mortar, cavity ties, ashings Fibre cement weatherboard Wooden panelling External rendering | 94 | 100 |
| **Scheuer et al.** (Scheuer et al. 2003) | USA | 39 | Other | aluminium/glass curtain wall, partially concrete masonry unit/brick facing, glass fibre heat | 1 | 75 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | insulation, U-value 0.134W/m² K (0.043 Btu/h ft2 F); fourth, fifth and sixth floor: pre-cast concrete planks, glass fibre heat insulation | | |
| **Suzuki and Oka** (Suzuki et al. 1995) | Japan | 40–49 | Res | wooden ,lightweight steel | 1253–22,982 | 40 |
| **Thormark** (Thormark 2002) | Sweden | 50 | Res | | 120 | 50 |
| **Winther and Hestnes** | Norway | 52–56 | Res | | 110 | 50 |
| **Winther** (Sartori 2008) | Norway | – | Office | Exposed brick | 4800 | 1 |
| **Zimmermann et al.** (Zimmermann et al. 2005) | Switzerland | 57–60 | Other | Diff. | Na.Avg. | 50 |
| **Fay et al.** (Fay et al. 2000) | Australia | 26–27 | Res | Brick, Timber | 128 | 100 |

Atsushi Takano(Takano et al. 2015) had done a similar kind research but for the cold climatic condition. And his method is to use only simulation model. The disadvantage of using simulation results alone cannot procreate such an advanced argument. Cole in 1996 had done a similar study and his intention is to under LCC of an office building. However, the methodology is almost similar to this study. Crawford, Robert 2011 study is very interesting because he has used one model and calculated all the materials used to build the house such as Material Bricks Carpet, nylon, Clear float glass (4 mm), Concrete 20 MPa, Concrete roof tiles (20 mm) Plasterboard (10mm).

Keoleian in 2001 studied LCC costing of different walling materials. This study was based on series of assumptions. For an instant, the study was not being conducted LCC for furniture house hold supplies etc. It was an inspiring study for this study to understand what to omit and their advantages of omitting for an LCC study. However, Mithraratne and Vale in 2004 have explained a method of developing life cycle costing model. Their study helped this study to develop a basic house model to calculate life cycle cost of the affordable house ( see the Paragraph 2.2).

Likewise there are many studies done in order to calculate life cycle cost of walling materials (see the figure 1), however most of them were done colder climates. Winther(Sartori 2008) from Norway has done his thesis in a similar study and most of his materials palette for colder climates. And contrary to available literature, only a few studies to understand affordable walling materials such as brick, cement block mud concrete blocks.

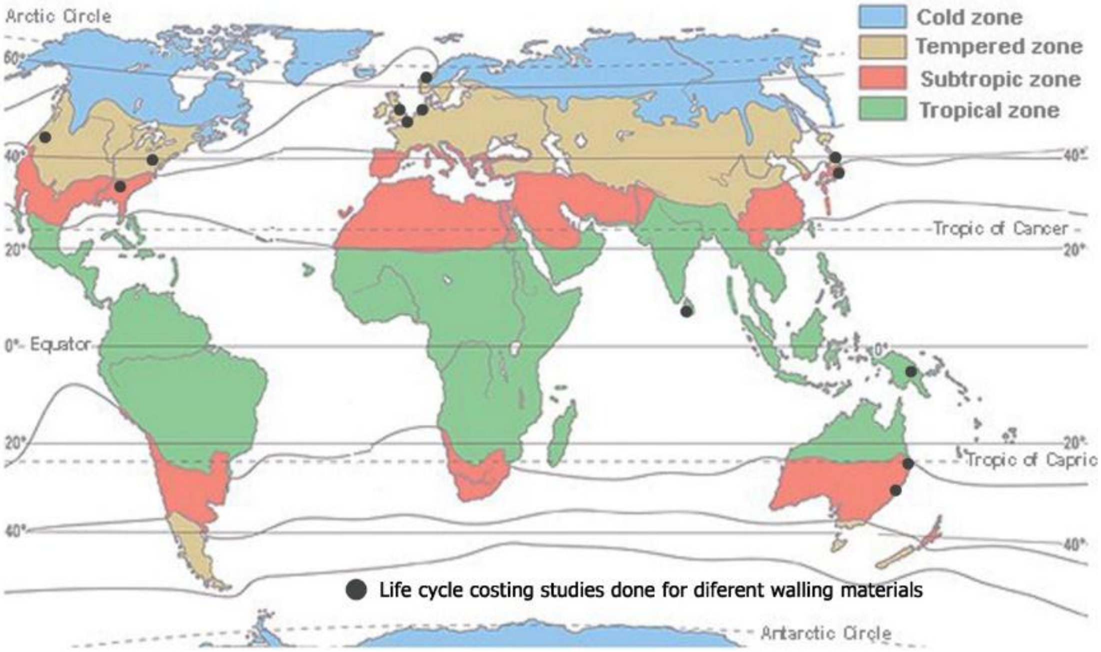



*Figure 1: Life cycle costing studies done in different climatic conditions*

# 2 Methodology

## 2.1 Selecting walling materials for the comparison

People tend to select solid walling materials such as brick, cement blocks, stones etc. due to the high solar radiation and heavy monsoon rain in tropical countries such as Sri Lanka. Not only the weather conditions but also the cost of construction is a key decision when selecting walling material in Sri Lanka. According to statistical data( figure 2; Central Bank of Sri Lanka 2016), (see most common walling materials are brick, hollow cement block and cabook details shown in the Table 2.And MCB (Mud Concrete Block) was added to the study since it's an uncommon and yet sustainable walling materials for affordable housing construction.

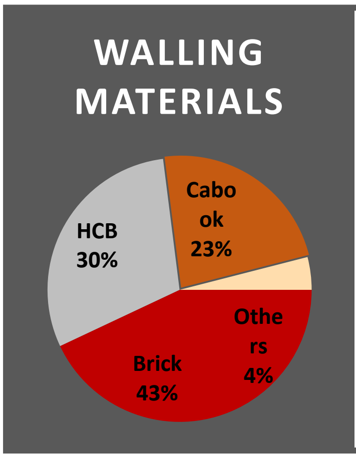



***Table 2: Selected walling materials properties and sectional details***

| **Block Name** | Dimensions | Wall thickness | Block Name | Wall thickness |
|---|---|---|---|---|
| | Length | Width | Height | |
| ***Brick*** | 215mm | 112.5mm | 65mm | 225mm (EB) |
| ***HCB*** | 200mm | 200mm | 200mm | 200mm(SB) |
| ***Cabook*** | 300mm | 200mm | 150mm | 200mm(SB) |
| ***MCB*** | 300mm | 200mm | 150mm | 200mm (SB) |

*Figure 2: Type of construction wall material (Income, H. (2014). Household Income and Expenditure Survey 2014-10.)*

However, walling materials such as timber posts steel sheets and wooden sheets were omitted from the research considering its structural changes due to the change in walling materials. And the wall thickness was considered as identical in all the buildings used to calculate the energy content and life cycle cost of the building. However, after the definition of all these walling materials, the energy content was analyzed accordingly. The next step of analyzing the walling materials is to compare and developed a base case for the comparison of walling materials analysis.

## 2.2 The base model for life cycle cost comparison

Figure 3 shows the Ministry of Housing & Samurdhi in Sri Lanka has launched a hundred-day program to develop hundred and fifty thousand houses in the country. Most of these house designs are built all over the country.

*Figure 3: Sri Lankan basic home built over the entire island*

These basic house models (Figure2) were given to poor locals by the Sri Lankan government as a manual of building their own house. The house manual was given to general public with a costing sheet and a material sheet. The house design was published by the national housing development authority and Samurdhi division. The basic home is consisted of following spaces and it's very simple for the general public to understand;

- Level site
- Floor area of 500 Sq. ft (46.4m$^2$)
- Two bedrooms with open plan living to dine together
- Separate bathroom shower
- 10 lights, seven power units, and three fans (Housing n.d.)(Housing & All 2011)

These houses shall be self-built and owned by them after the construction. And the owner shall be responsible for the long-term upkeep of the house such as plaster, paint etc. These buildings are being built in rural locations in Sri Lanka. Therefore, the study assumed that the building location is in a non-land sliding location where no precautions should be taken in order to prevent any building collapse within the total life span of the house.

## 2.3 Energy accounting and LCC calculation for basic house model

Preliminary Bills of Quantities (BOQ) were calculated in order to account a number of materials required to build the basic house model. Accession the costing was done in order to understand the cost variation of different walling materials. Subsequently, the total energy account was transformed into the life cycle model where the total energy consumption of a period of sixty years (one life span) was calculated considering the maintenance and replacement energy cost.

### 2.3.1 LCC accounting for period of sixty years

The sixty-year life span of the affordable house was defined by using British standards(Institution 1992)(Dias 2013). The sixty-year definition helps the research to omit unnecessary calculation. However, all the selected walling materials have the life span more than sixty years, therefore, the replacement cost of walling materials was neglected from the LCC calculation process. However, necessary maintenance cost was included while calculating the total life-cycle cost of the building. Hence, the total life cycle cost is calculated by using following equation 1.

$$LCC = IC + (MC + EC + Oc) + Uc - Rv \qquad (1)$$

### 2.3.2 U values of different waling materials used in this study

***Table 3: U-value calculations of different walling materials***

| **walling materials** | U value | Reference |
|---|---|---|
| **Brick** | 2.110 W/m$^2$K | (Rohintan. Emmanuel 2004) |
| **HCB** | 2.617 W/m$^2$K | (Hall 2015) |
| **Cab** | 3.756 W/m$^2$K | (measured and tested via simulations) |
| **MCB** | 2.315 W/m$^2$K | (measured and tested via simulations) |

Brick and HCB are popular walling materials in the world. Therefore, there are many types of research done and the heat conductivity is measured. However, cabook and mud concrete block are not popular walling materials in the country. Cabook is an eco-friendly walling material made of hard soil blocks. MCB is a novel walling material invented by the university of Moratuwa (Sri Lankan Patent No-17216)(Halwatura 2016)(Arooz et al. 2015).Therefore, cabook and MCB thermal conductivity should be measured in order to continue this research.

In order to understand the actual thermal conductivity of these waling material, real world model houses (see the Figure 4) were built.. Their thermal performances were tested by using thermal data loggers(Udawattha & Halwatura 2016c).

*Figure 4: One-meter house models made to calibrate thermal conductivity coefficient*

At the same time, the coefficient of thermal performances was measured by using thermal conductivity tester (see the Table 4). Therefore, the calibration of the thermal conductivity had double checked. Thence, the measured thermal performance of the real world scale model is simulated by using the thermal conductivity meter and calibrated by using simulation software.

***Table 4: Measuring coefficient of thermal conductivity***

| Cab Wall samples conductivity testing | MCB Wall samples conductivity testing |
|---|---|
|  |  |



The measurement field was carried out by using the guidance given by the manufacturer of the thermal conductivity coefficient meter. The final figure for the Cabook and MCB (see the *Table 3*) U-values were defined by using design builder model, calibrated to match with real world conductivity.

### 2.3.3 Calibrating U values measured by using thermal conductivity meter.

A thermal conductivity meter is not efficient enough to make a conclusion of the thermal conductivity. Therefore, the separate simulation was carried out to confirm the thermal conductivity of Cabook and MCB. For that, the model houses measured thermal performance was simulated and calibrated. Thence, all the walling materials were simulated on one affordable house model shown in Figure 5.

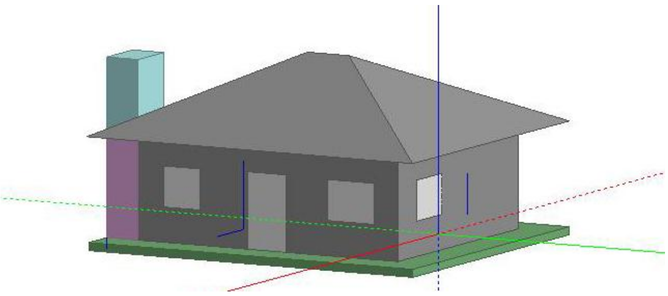


*Figure 5: Design-Builder model used simulate cooling load for period of sixty years*

## 2.4 Investigation on life span of different waling materials

Before understanding life cycle cost of different walling materials. The usable life span of these walling materials was measured and tested by using accelerated weather testing.

# 3 Results

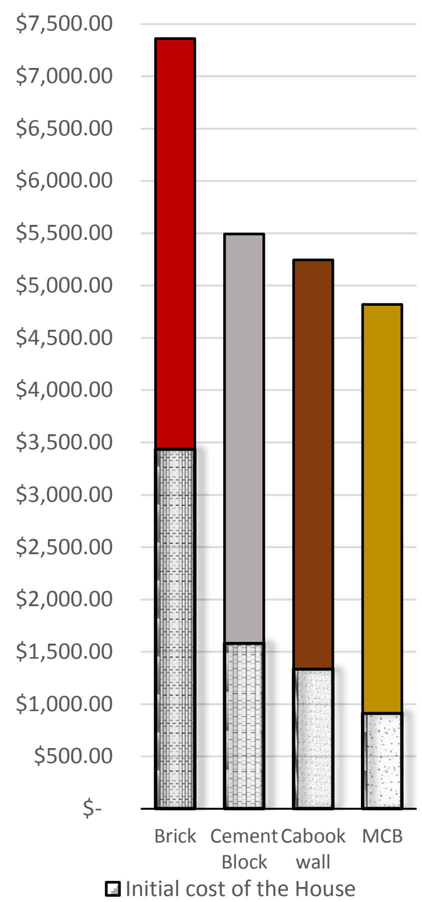
## 3.1 Embodied energy

***Table 5: Embedded energy calculation for 570Sqft. House***

| Item | Material | Brick | HCB | Cabook wall | MCB |
|---|---|---|---|---|---|
| **Foundation** | Random rubble | 3516.5 MJ | 3516.5 MJ | 3516.5 MJ | 3516.5 MJ |
| **Wall** | | 177872 MJ | 195221MJ | 31218 MJ | 28611 MJ |
| **Roof Work** | clay tile | 480408.5 MJ | 480408.5 MJ | 480408.5 MJ | 480408.5 MJ |
| **Doors & Windows** | wood | 985.4 MJ | 985.4 MJ | 985.4 MJ | 985.4 MJ |
| **Floor concrete** | concrete | 6603.6 MJ | 6603.6 MJ | 6603.6 MJ | 6603.6 MJ |
| **Bathroom** | Bathroom fittings | 1840.9 MJ | 1840.9 MJ | 1840.9 MJ | 1840.9 MJ |
| **Electrical** | Fittings | 10676.0 MJ | 10676.0 MJ | 10676.0 MJ | 10676.0 MJ |
| **Internal wall plastering** | Cement mortar | 421.4 MJ | 421.4 MJ | 421.4 MJ | 421.4 MJ |
| **Internal Painting Work** | Emulsion paint | *NTA* | *NTA* | *NTA* | *NTA* |
| **External wall plastering** | Cement mortar | 283.1 MJ | 283.1 MJ | 283.1 MJ | 283.1 MJ |
| **External Painting Work** | Emulsion paint | | | | |
| **Septic tank** | Precast concrete | 80.6 MJ | 80.6 MJ | 80.6 MJ | 80.6 MJ |
| **Total material embedded energy** | | 682688 MJ | 700037 MJ | 536034 MJ | 533427 MJ |

Embodied energy in selected walling materials calculated without the internal and external plaster work. Plastering work was calculated separately to understand the materials contribution to the total embodied energy of the house. It was assumed that all the walling material constructed with the similar smooth finish. In addition, stretcher bond was used to build all four types of walls (see the ***Table 5***).

It was assumed that all the labor was available within the site. The mortar was mixed at the same place where the brick wall was being built. Mortar mixings did by using human labor, no machinery is being used whatsoever while building the house wall.



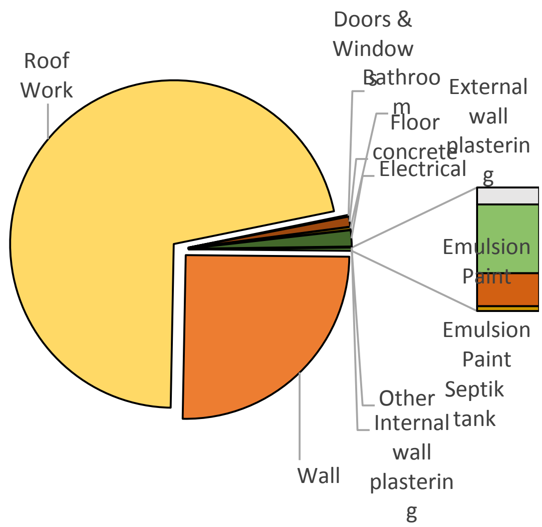




*Figure 6: embedded energy comparison (MJ)*▲

◄*Figure 7: Initial cost and walling material cost*

*Figure 6 clearly shows that roofing material and walling material mostly contribute to the total account of embedded energy in the house. The comparison of different walling materials (see the* ***Table 5****) shows that Brick has the highest embedded energy content and cement shows the second highest embedded energy. The Cabook, which is the only 100% natural walling material has the lowest embedded energy because of it is eco-friendly.*

The brick has the highest embedded energy on account of the biomass used to manufacture bricks in Sri Lanka (Dias 2013). However, mud concrete block as a walling materials and best substitute for the brick and hollow HCB shows the comparative lowest embedded energy (Udawattha & Halwatura 2016a).

### 3.2 Initial cost and walling material cost

The initial cost of different walling materials was taken into consideration in respect to the total cost of the building. The ratio of the walling materials cost indicates the economic feasibility of the walling materials. The higher the percentage, which included to the walling materials are lower in economic sustainability.

Considering results shown in ◄Figure 7 **Error! Reference source not found.**, walling materials such as brick and HCB are exceptionally expensive. At the same time, they are contributing an expectant amount to the total cost of the house (see the ◄Figure 7 **Error! Reference source not found.**). Therefore, walling materials such as mud concrete block are much more cost effective. However, the real analysis should consider the effect of walling material in the long run. The cooling load is calculated basically to calculate the sustainability of different walling materials.

### 3.3 Cooling load calculations

The cooling load was calculated by using design builder energy simulating model shown in Figure 5. The wall thickness and exterior surfaces were defined considering the materials property of the wall. For an example, walling materials such as mud concrete block do not need an exterior plaster.

The computer-based simulations were used to calculate the annual cooling load of the house. The houses are not designed for the active cooling systems, therefore, the average cooling load of the house is combatively higher. Merely this investigation comparing the similar model, the efficiency of the cooling load simulations was omitted. U value and the thickness of the material were used as the key changes in the similar model (see the Figure 5).

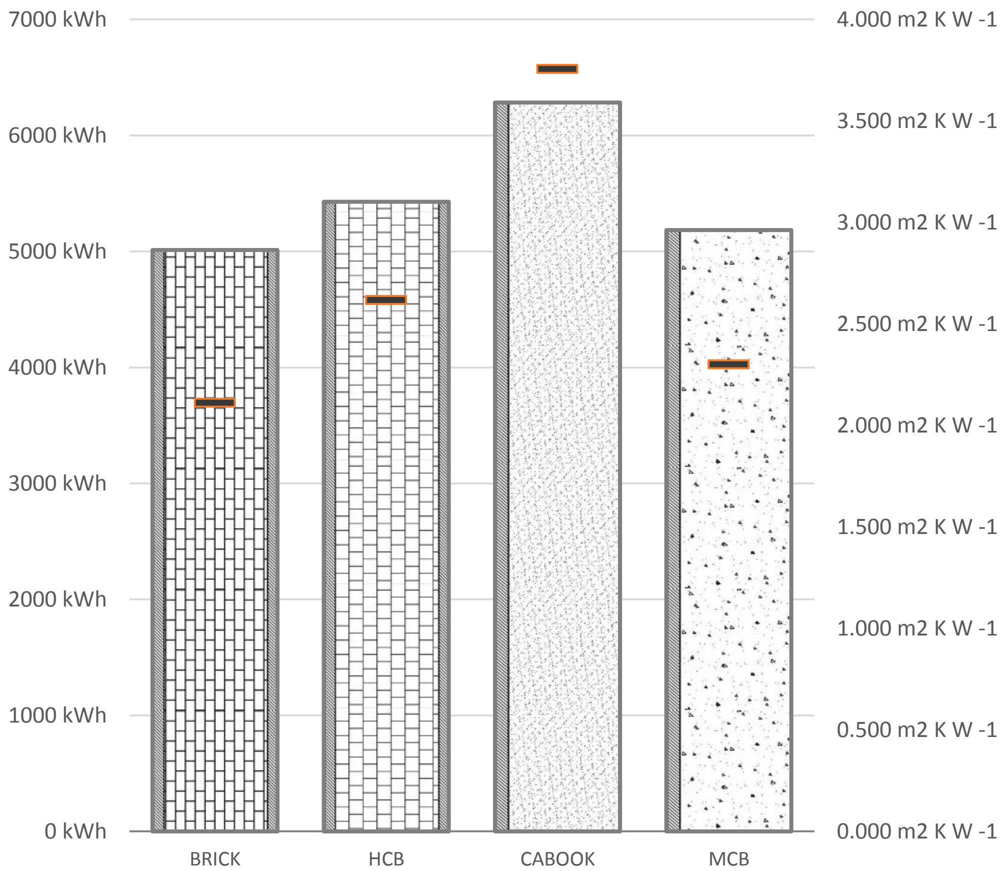



*Figure 8: Cooling Load calculation for period of sixty years and their U values*

The annual cooling load was converted into money value by considering the cost per one-kilowatt shown in Table 8. Then the money value of cooling load per year calculated for a period of sixty years by using present worth annuity formula.

### 3.3 Reusability and Resale value

The purpose of measuring reusability and resale value is to calculate the durability of different walling materials, therefore, the reusability factor is important. However, the reusability was measured only for the similar usage in the future and the land value was omitted since the land value is not important for this comparison. While calculating the reuse of building materials the other alternative reuses or recycle were omitted because of their complexity in alternative reuses. *Table 6* Reusability and resell value indicates the resell value and reusability of different walling materials. The other building components were measured to understand the total life-cycle cost of the building.

The reusability and the resale value studied locally by using different materials costing models. And old buildings were used to develop the study. Not only for the walling materials but also for the other building elements life span was measured. The Housing authority housing program helped to study the durability and reusability different building materials in Sri Lanka.

*Figure 9: Calculating reusability factor of building materials*

(see the *Table 6*)

In order to understand the suitability of walling materials after using for the first time. And it was assumed that the total lifespan of the building is sixty years and more than sixty-year life span building materials were multiplied by the reusability factor.

***Table 6: Comparison of reusability and resale value***

| | Brick | HCB | Cabo | MCB |
|---|---|---|---|---|
| **Reusability** | 60% | 70% | 60% | 92% |
| **Resale Value** | $1,739.79 | $1,105.70 | $887.50 | $971.96 |

### 3.4 Life cycle cost

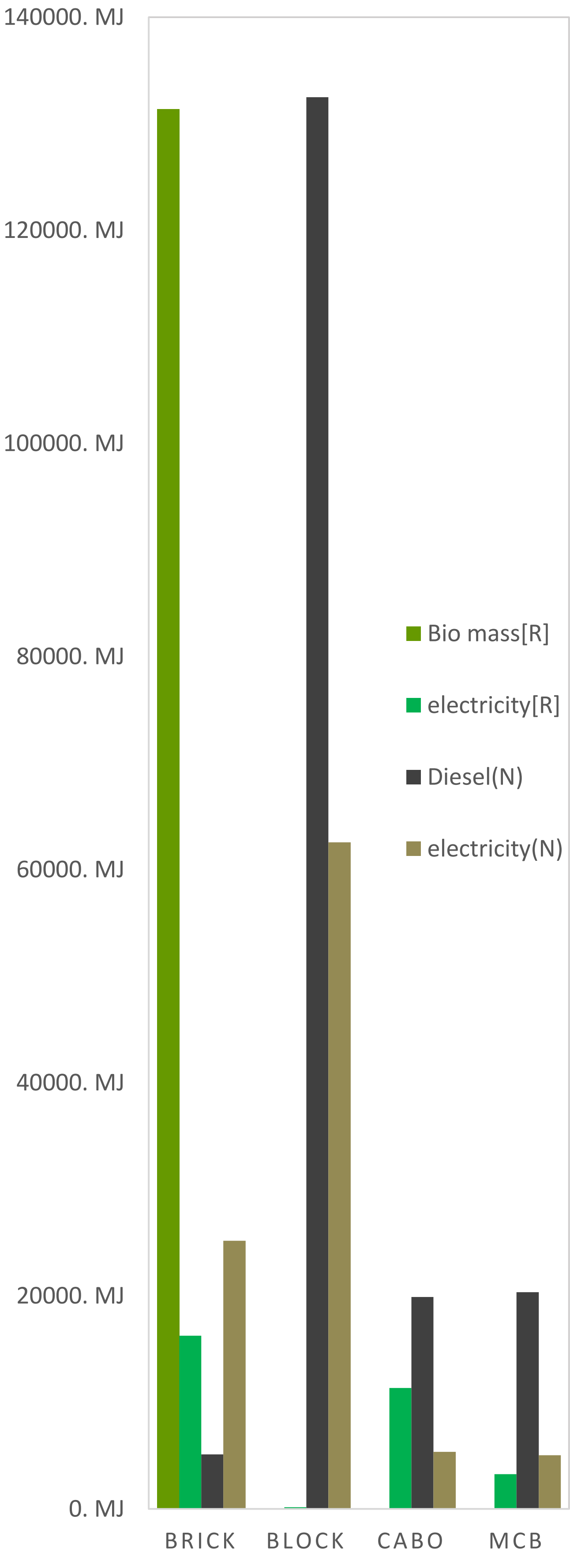
Life cycle cost, of course, a combination of all the cost incurred from construction to the end use of the building. The LCC comes from three different stages in the building suing process initial cost, maintenance cost, and replacement cost (see the equation 1). The reusable material cost was deducted from the total cost and calculated the total life-cycle cost of the building. Perhaps most of these building materials are recyclable and reusable for another use. However, considering calculation the recycle cost and resale cost of different usages were omitted (see the Table 8).

## 3.5 Carbon dioxide emissions of different walling materials.

The carbon foot print of different walling materials was calculated by converting the energy into carbon. The conversion factor of energy to carbon was developed by using local study data(Pooliyadda & Dias 2000). The number of blocks and their weight was calculated separately in the Figure 10. The energy consumption per block was calculated by the author in a separate study(Udawattha & Halwatura 2016a), and then the energy per block and carbon per block was equated. The final outcome of the energy and carbon footprint per the entire house was calculated to understand the carbon foot print of the wall materials (see the Table 7).

***Table 7: Carbon dioxide emissions of different walling materials.***

| Wall type | Energy MJ per blocks | Energy MJ per wall construction | Carbon (KgC) per block | Carbon (KgC) per wall construction |
|---|---|---|---|---|
| **Brick** | 177871.71 | 178723.09 | 0.035304348 | 467kgC |
| **HCB** | 195220.58 | 132744.22 | 0.52125 | 480kgC |
| **CABO** | 31218.32 | 52750.50 | 0.096363636 | 244kgC |
| **MCB** | 28610.76 | 41145.00 | 0.042384106 | 147kgC |



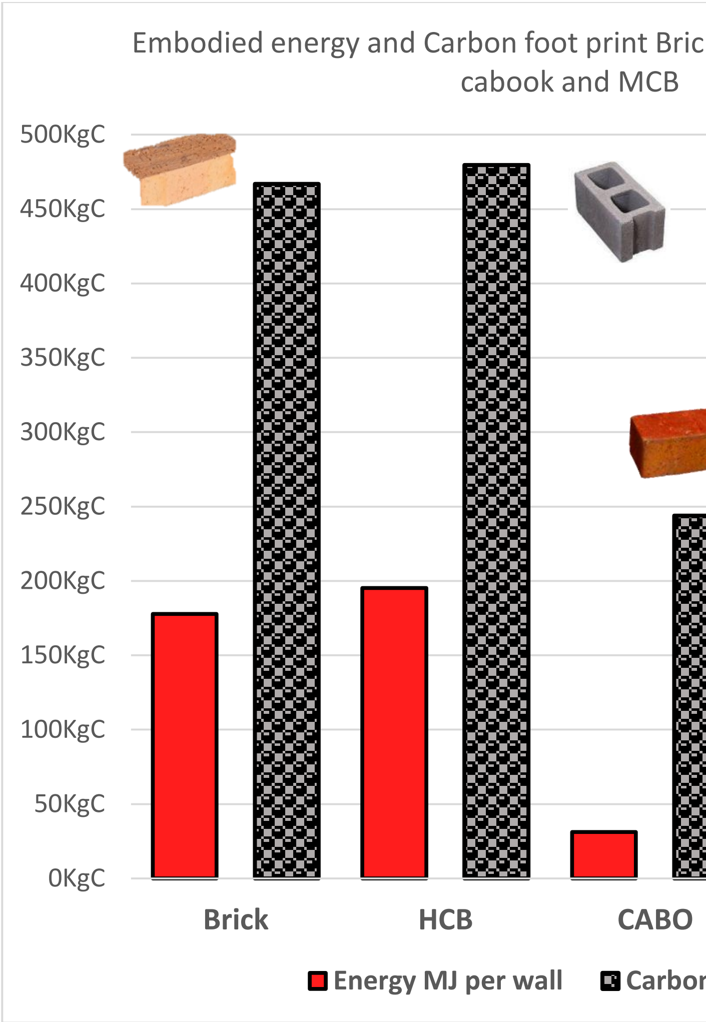




*Figure 10: carbon dioxide emissions and embodied energy of different walling materials*

### 3.6 Fuel source and environmental suitability of energy source

The energy content of the different waling material to build affordable house model was measured and developed (see the Table 5) and then another study was done in order to calculate the carbon foot print of each and every walling materials used to build affordable housing in the country. Even though, study was aimed to calculate the LCC of different walling materials, which is very important to understand the environmental suitability of these walling materials. Thence the energy source and the sustainability of the energy source was measured and equated in the Figure 11).

It was found that most of the energy used to construct walls are not renewable. Most the energy was spent in the manufacturing process and the transport process. Since the Bricks are made in coconut husk kiln, and they seem using more renewable energy than other walling materials.

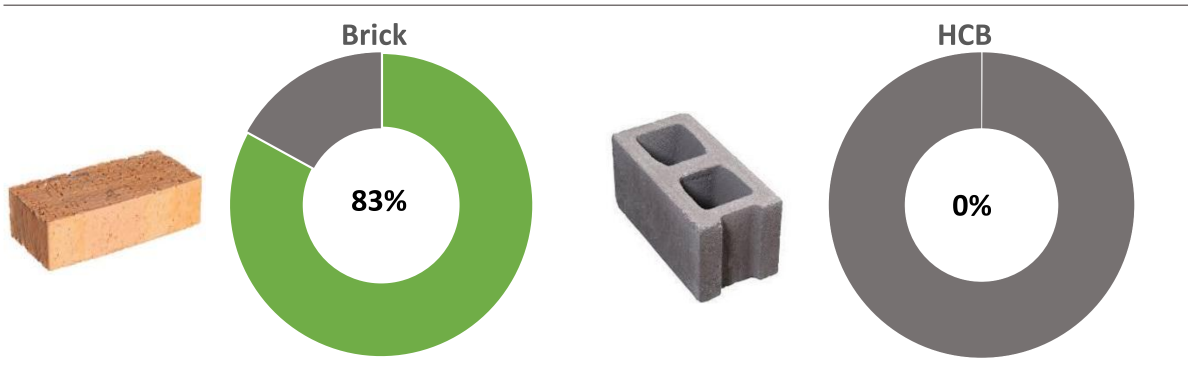
Brick consumes more energy with higher carbon footprint, its energy source is much more sustainable than HCB. And the walling materials such as Cabook and Mud concrete block are eco-friendly since they are using less amount of carbon-based energy sources. It's only nonrenewable energy coming from the transportation and the construction electricity such as cutting and grinding at the site.

Hollow cement block is most non-renewable energy consumer. Its energy source is not environmental suitable thus cannot be replaced with another energy source since the HCB is produced by crushed gravel particles made of heavy diesel grinders.

*Figure 11: The fuel source of selected walling materials*

### 3.6.1 Environmental suitable of the walling construction energy

Any product or service is an outcome of the lengthy production process. The production process consume energy to change raw materials into finished product. In this study, the final product is the constructed wall for the affordable house model. Thence, the environmental suitability can be measured by the energy source renewability. Because the renewable energy is favorable for the environment and promotes sustainability. The initial energy source calculation was used to understand the environmental suitability of the walling materials. And then the renewable energy sources highlighted as a percentage to understand the environmental suitability (see the Figure 12).



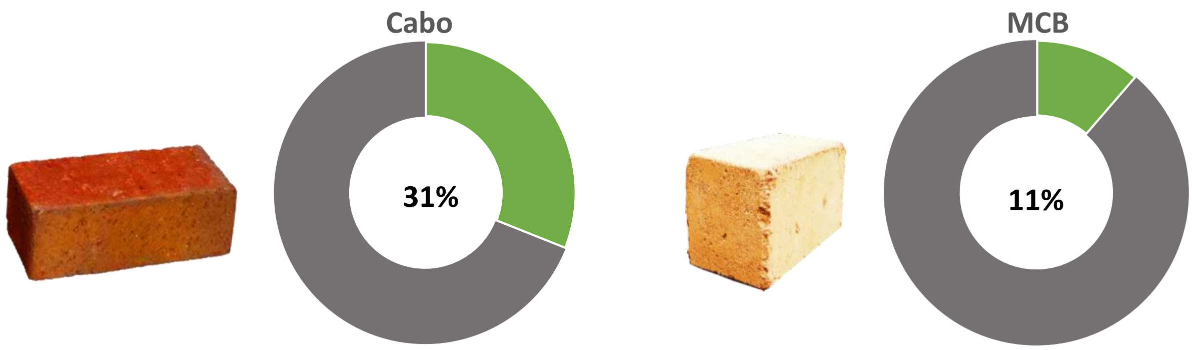



*Figure 12: Environmental suitability of different walling materials*

### 3.7 Suitability Index (SI)

Finally, all the results were taken into one table in order to understand the suitability of walling materials to build affordable housing in Sri Lanka (see the Table 8).

*Table 8: Overall results of different waling materials*

| | Brick | HCB | Cabook wall | MCB |
|---|---|---|---|---|
| **Embedded energy** | 178723 MJ | 195221 MJ | 52750 MJ | 41145 MJ |
| **Carbon (kgC) per wall construction** | 466.9 | 479.55 | 243.8 | 147.2 |
| **Environmental suitability** | 83% | 0% | 31% | 11% |
| **Total initial cost** | $7,335.09 | $5,480.05 | $5,379.64 | $4,956.95 |
| **Total energy cost** | $37,598.99 | $40,719.11 | $47,139.36 | $38,889.04 |
| **Life cycle cost** | $47,234.37 | $48,351.05 | $54,662.86 | $45,956.04 |

The extended analysis is to understand the overall comparison of this study. Table 8 shows the concluding comparison of different properties of different wallings materials. A suitable rank was given according to the property of walling materials. The rank was given considering the best case as the reference and coming to the worse case value as a percentage (see the equation 2). And then similar method applied all the values and taken the average as the walling materials suitability index to affordable housing in Sri Lanka.

$$Walling\ materials\ suitability\ index\ (Si) = \frac{The\ value}{The\ value\ of\ the\ best\ case} \times 100$$

(2)

The lowest embedded energy walling material is the best case and rest were ordered simultaneously. The initial cost, energy cost, carbon footprint, environmental suitability and Life cycle cost were ordered from starting the lowest to the highest. However, the approximation was to make a determination out of the results taken by this investigation.

*Table 9: Sustainability rank of different walling materials*

| Hierarchy of indexes | | Brick | HCB | CABO | MCB |
|---|---|---|---|---|---|
| **01** | Initial cost | 4 | 3 | 2 | 1* |
| **02** | Life cycle cost | 2 | 3 | 4 | 1* |
| **03** | Operation energy cost | 1* | 3 | 4 | 2 |
| **04** | Embedded energy | 3 | 4 | 1* | 2 |

| | | | | | |
|---|---|---|---|---|---|
| **05** | Environmental suitability | 1* | 4 | 2 | 3 |
| **06** | Carbon Foot print | 4 | 3 | 1* | 2 |
| | **Overall Rank** | **[2]** | **[4]** | **[3]** | **[1]*** |

*The best case

The overall rank was given in the Table 9 considering the priority of above-mentioned suitability indexes.

The priority was the initial cost since the study aimed to affordable housing. And then the life cycle cost and operation energy cost. The fourth environmental suitability and the last is the carbon footprint. Table 9 shows the overall results and the overall rank to select best walling materials to build affordable houses.

## 4 Conclusions

This study assays to evaluate the environmental sustainability of different walling materials used to build affordable houses in Sri Lanka. The walling materials were selected by considering their similarities and the popularity in the local market; Brick, HCB, Cabook and Mud concrete block. Mud concrete block is a novel alternative walling.

One of the crucial findings of this study is reusability of the walling material. The wall can be suitable in embedded energy and the initial cost. However, if they are not strong enough for the reuse, there is no suitability of them in respect to environmental sustainability. Merely for walling materials, brick mud concrete block can be reused over and over again for the similar use. Mud concrete block is 92% reusable. Its ingredient can be crushed and produce same walling material with an addition of cement ratio of 8%. Therefore, MCB and Brick are environmentally suitable than other walling materials such as HCB and CAB. Considering all the scales given to measure the suitability of different walling materials such as embedded energy initial cost operation cost and Life cycle cost; Mud concrete block is the best walling materials to build affordable houses. Carbon dioxide emission is another study carried out and results shows that CABO earth waling materials have the lowest carbon emission because its extracted from the earth. And the brick is worse carbon emitting walling materials.

The overall rank was given considering the best case and found that Mud concrete block is best suitable walling materials to build an affordable house. Cabook is the second best walling materials since its low cost and the low emission of carbon and consumes less amount of energy. However, in contrary to the second best case of Cabook has many limitations such as lack of resources to produce Cabook in the local market. However, the brick and the hollow cement block are the worse building material. The brick seems better than HCB since the brick is produced by using coconut husk clean energy. However, its embodied energy and the life cycle cost if comparative higher than MCB and Cabo. Not only the embodied energy but also the reusability also little lower than other waling materials. And the hollow cement block made of quarry dust need a lot more non-renewable energy to produce. Therefore, overall the Hollow cement block is the worse building materials to suit into tropical climate condition like Sri Lanka.

## 5 Limitations

The materials source and the environmental impact should be taken into consideration in order to define the sustainability of a walling material. The environmental impact and its pollution were neglected. The other limitations are the social impact due to the selection of a particular waling materials was disregarded alongside the study. Because the social impact cannot be assessed along with engineering parameters. The other limitations is the practicality of the walling materials was neglected. The constructability availability of skilled labor to build the walling types and the manufacturing framework was neglected.

## References


Adalberth, K., 1997. Energy use during the life cycle of buildings: a method. *Building and Environment*, 32(4), pp.317–320. Available at: http://www.sciencedirect.com/science/article/pii/S0360132396000686.

Arooz, F.., Ranasinghe, A.W. & Halwatura, R.U., 2015. Mud – Concrete Block Construction , Community centers for war victim communites in Batticaloa, Sri Lanka. In *Making built environments responsive*. Colombo, Sri Lanka: Faculty of Architecture Research Unit, University of Moratuwa, Sri Lanka, pp. 186–200.

Central Bank of Sri Lanka, 2012. National output and expenditure. *Annual Report 2012*, pp.1–30.

Chen, J., Hao, Q. & Stephens, M., 2010. Assessing Housing Affordability in Post-reform China: A Case Study of Shanghai. *Housing Studies*, 25(6), pp.877–901. Available at: http://www.tandfonline.com/doi/abs/10.1080/02673037.2010.511153 [Accessed March 19, 2017].

Cole, R.J. & Kernan, P.C., 1996. Life-Cycle Energy Use in Office Buildings. , 31(4), pp.307–317.

Crawford, R.H., 2011. Life Cycle Water Analysis of an Australian Residential Building and Its Occupants. , p.10.

Dias, W.P.S., 2013. Factors Influencing the Service Life of Buildings. *Engineer*, XXXXVI(4).

Dutil, Y. & Rousse, D., 2012. Energy costs of energy savings in buildings: A review. *Sustainability*, 4(8), pp.1711–1732.

Fay, R., Treloar, G. & Iyer-Raniga, U., 2000. Life-cycle energy analysis. *Building Research & Information*, 28(1), pp.31–41.

Feist, W., 1997. Life-Cycle Energy Analysis: Comparison of Low-Energy House, Passive house, Self-Sufficient House. *Passive House Institut*, p.13.

Gao, W. et al., 2001. Energy impacts of recycling disassembly material in residential buildings. *Energy and Buildings*, 33(6), pp.553–562.

Hall, F., 2015. *Building Services and Equipment, Volume 2*, Routledge. Available at: https://books.google.com/books?id=6TuLCgAAQBAJ&pgis=1 [Accessed March 13, 2016].

Halwathura, R., 2016. AN-II_PATENT-MCB (1).pdf. , p.5.

Hamidul Islam D, 2012. *Use of Material in Residential House Design: An Optimisation Approach Balancing Life Cycle Cost & Life Cycle Environmental Impact Hamidul Islam*.

Housing, J. & All, F., 2011. " JANASEVANA " National Housing Symposium 2011 and Common Amenities.

Housing, M.O.F., *100 Days Fifty Thousand Accelerated Housing Development Programme*,

Institution, M.K., 1992. BS 7543: Guide to Durability of Buildings and Building Elements, Products and Components. *British Standard Institution*, pp.1–8.

Keoleian, G. a, Blanchard, S. & Reppe, P., 2001. Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House. *Journal of Industrial Ecology*, 4(2), pp.135–156.

Li, Z., 2006. A new life cycle impact assessment approach for buildings. *Building and Environment*, 41(10), pp.1414–1422. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132305001903 [Accessed October 17, 2015].

Mithraratne, N. & Vale, B., 2004a. Life cycle analysis model for New Zealand houses. *Building and Environment*, 39(4), pp.483–492. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132303002191 [Accessed October 11, 2015].

Mithraratne, N. & Vale, B., 2004b. Life cycle analysis model for New Zealand houses. *Building and Environment*, 39(4), pp.483–492. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S0360132303002191.

Pooliyadda, S.P. & Dias, P., 2000. *Energy Content and Carbon Emission*. University of Moratuwa.

Rohintan. Emmanuel, 2004. Estimating the environmental suitability of wall materials preliminary results from Sri Lanka. *Building and Environment 39*, 39, pp.1253–1261.

Sartori, I., 2008. *Modelling energy demand in the Norwegian building stock*,

Sartori, I. & Hestnes, a. G., 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, 39(3), pp.249–257. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778806001873 [Accessed December 17, 2014].

Scheuer, C., Keoleian, G. a & Reppe, P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy and Buildings*, 35(10), pp.1049–1064. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778803000665 [Accessed October 12, 2014].

Stone, M.E., 2006. What is housing affordability? The case for the residual income approach. *Housing Policy Debate*, 17(1), pp.151–184. Available at: http://www.tandfonline.com/doi/abs/10.1080/10511482.2006.9521564 [Accessed March 19, 2017].

Suzuki, M., Oka, T. & Okada, K., 1995. The estimation of energy consumption and CO 2 emission due to housing construction in Japan. *Energy and Buildings*, 22(2), pp.165–169. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-0000905050&partnerID=40&md5=26320e47d8279798ef236aaacd22bd5a.

Takano, A. et al., 2015. The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland. *Building and Environment*, 89(March), pp.192–202.

Thormark, C., 2002. A low energy building in a life cycle — its embodied energy , energy need for operation and recycling potential. , 37, pp.429–435.

Udawattha, C. & Halwatura, R., 2016a. Embodied energy of mud concrete block (MCB) versus brick and cement blocks. *Energy and Buildings*, 126, pp.28–35. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778816303243.

Udawattha, C. & Halwatura, R., 2016b. The embodied energy and life cycle costing: A case study on basic dwellings in Sri Lanka. In *National Green Conference 2016 at University of Kelaniya*. pp. 1–10.

Udawattha, C. & Halwatura, R., 2016c. Thermal performance and structural cooling analysis of brick , cement block , and mud concrete block. *ADVANCES IN BUILDING ENERGY RESEARCH, 2016*.

VARGHESE, P.C., 2015. *BUILDING MATERIALS*, PHI Learning Pvt. Ltd. Available at: https://books.google.com/books?hl=en&lr=&id=fQy_CAAAQBAJ&pgis=1 [Accessed April 7, 2016].

Yang, L., Yan, H. & Lam, J.C., 2014. Thermal comfort and building energy consumption implications – {A} review. *Applied Energy*, 115, pp.164–173. Available at: http://www.sciencedirect.com/science/article/pii/S0306261913008921.

Zabalza Bribián, I., Aranda Usón, A. & Scarpellini, S., 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, 44(12), pp.2510–2520.

Zimmermann, M., Althaus, H.J. & Haas, A., 2005. Benchmarks for sustainable construction: A contribution to develop a standard. *Energy and Buildings*, 37(11 SPEC. ISS.), pp.1147–1157.