Eco-efficiency assessment of conventional OPC/PPC replacement by LC3 in Cuban residential buildings

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Abstract. This paper aims at assessing the sustainability of replacing conventional OPC/PPC by Limestone Calcined Clay Cement (LC3) in Cuba. Authors conducted an eco-efficiency (E-E) analysis supported by E-E ratios, which in turn are rooted on the environmental assessment (Life Cycle Assessment, LCA) and the economic analysis (Economic Value Added, EVA). Taking case studies in Villa Clara province capital district, three construction methods were compared and further conclusions emerged with regard to economic and ecological criteria. A square meter of built area was employed as functional unit. According to main results, Gran panel technique appears to be the benchmarking method, followed by Forsa system and, finally, concrete block technique. LC3 blend outperforms OPC/PPC from both economic and environmental perspective. Furthermore, productive efficiency potentials were found on the field of material selection and raw material procurement. Authors provided decision-makers with some policy recommendations in order to contribute enhancing the sustainable use of LC3 in Cuban construction sector.

1. Introduction
The building materials sector is the third-largest CO2 emitting industrial sector worldwide [1]. This sector represents 10% of the total anthropogenic CO2 emissions, most of which are related to concrete manufacture: about 85% of these CO2 emissions come from the provision of cement [2]. Due to the responsibility of construction activities on climate change, the global concern has been focused on the production of concrete structures. Modern civilisation construction is mainly built of concrete, the most consumed material in the world, after water. For emerging economies —where the building stock is still under construction and the potentials for renewable energy transition are not already proven— the need for alternative materials is increasingly recommended.

LC3 —Limestone Calcined Clay Cement— is a blended cement innovation proposed by an international team led by the Swiss Federal Institute of Technology, EPFL-Lausanne. LC3 is a combination of clinker (50%), calcined clay (30%), gypsum (5%) and limestone (15%). The calcined clay of this newly developed technology is metakaolin. Metakaolin has been gaining attention among cement producers as a supplementary cementitious material [3]. Abundant information is readily
available on the literature, i.e., [4],[5],[6]. LC3 advantages not only lie on the energy reduction field and emission savings; moreover, it leads to approximately 15% cost-cutting.

This paper aims at assessing the sustainability of replacing conventional OPC/PPC by LC3 in Cuba. Three construction methods have been taken into consideration: (i) concrete block technology, (ii) Grand panel system (mainly prefabricated concrete elements) and (iii) Forsa system (mainly RMC-intensive). The aforementioned building systems were analysed along the following three scenarios: (i) Business As Usual (BAU scenario), which means producing/using conventional OPC/PPC cements, (ii) the country only replaces PPC by LC3, (iii) LC3 substitutes both existing cements. All the alternative choices are scrutinised by taken into account the eco-efficiency index early proposed by [7],[8],[9]. The ratios were built upon the results of Life Cycle Assessment (LCA) and Economic Value Added (EVA) as two so-called and so-accepted ways of looking at sustainability pillars.

Authors looked at the economies of scale coming from different building sizes, as well as the transportation distance breakeven point for building materials costing. Finally, some policy recommendations arisen from the results of four case-studies, were reached.

2. Methodology and data
The eco-efficiency index was calculated by means of the Equation 1, as proposed in the sustainability literature. Data sources for calculating LCA are twofold: background data took impact factors from previous researches [10],[11],[12] and foreground data is reported in table 1. Figure 1 shows the breakdown of material consumption according to the four case-studies under assessment in this paper.

\[
Eco\text{-efficiency index} = \frac{EVA \ (Economic \ Value \ Added)}{CO_2 \ (Carbon \ Dioxide \ Emissions)} \quad (Eq.1)
\]

### Table 1
Foreground data for the case studies under assessment

| Building materials/Building system | Blocks | Grand Panel | Forsa |
|-----------------------------------|--------|-------------|-------|
|                                   | Unit   | Two-storey  | Two-storey | Five-storey | Five-storey |
| Ready-Mix Concrete               | m³     | 30,6        | 10,9      | 40,1        | 397,0       |
| Prefabricated concrete           | m³     | 9,5         | 52,0      | 277,8       | 14,3        |
| Blocks 15 cm                     | u      | 7560,0      | 770,0     | 2381,0      | 2140        |
| Cement                           | t      | 29,3        | 8,6       | 40,2        | 27,7        |
| Sand                             | m³     | 42,9        | 30,1      | 79,3        | 55,0        |
| Gravel                           | m³     | 0,37        | 0,9       |             |             |
| Calcium hydrate                  | t      | 4,92        | 2,25      | 9,9         | 6,8         |
| Steel                            | t      | 2,83        | 0,86      | 2,6         | 31,5        |
| Usable floor area                | m²     | 168,74      | 161,42    | 863,6       | 806,9       |

Data on table 1 stands for the data inventory needed to conduct LCA as well as the economic assessment. The amount of cement reported in row 4 is the cement used for mortar in masonry applications. The cement consumption per unit of building materials listed on the above table, behave as follows: 450 kg per cubic meter of ready mix concrete, 360 kg per cubic meter of precast concrete and 1,62 kg per block. Figure 1 reports the breakdown of construction materials consumption by construction technology type, expressed in percentage. It shows that Grand panel system is prefab-intensive while Forsa method is quite RMC consuming. Concrete block technique is mainly based on...
masonry applications, which require a great amount of cement in the construction site. The later system is labour-intensive and needs to mobilize the transportation of a huge amount of building materials.

![Material consumption breakdown, by construction technology type (percentage).](image)

**Fig. 1.** Material consumption breakdown, by construction technology type (percentage).

3. **Results**

Figure 2 summarizes the eco-efficiency outputs of this study. Some concluding insights would be drawn from the results:

![Eco-efficiency index comparison for the case studies being assessed](image)

**Fig. 2.** Eco-efficiency index comparison for the case studies being assessed

- Grand panel seems to be the most eco-efficient construction technology within the case studies under examination, which represents an intermediate level of industrialisation in between the concrete block system and Forsa technology.

- By inspecting the two building sizes within Grand panel technique, some potentials for economies of scale are achieved: up to 15% cost reduction would be possible to attain, strictly coming from the building size. It also contributes reducing the land use, therefore, the ecological footprint of mankind construction activities.

- LC3 would be more effectively used in RMC-intensive choices from a sustainability viewpoint, but it always must be seen in light of raw materials transport distances.
\textit{Ceteris paribus} the cement type used for construction, the cost of transporting raw materials needs for attention, particularly for those economies like Cuba where the productive efficiency depends upon the transportation parameters. Material selection in construction sector is crucial because of the enormous volume and mass needed to be transported. That is why the nearness of raw materials deposits constitutes a core piece of the cost analysis.

The figure 3 describes an estimated transport cost function for raw materials, according to those case-studies under assessment. Detailed calculations can be found in [4].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{transportation_cost_function}
\caption{Transportation cost function at the level of raw material}
\end{figure}

In a second step, using (i) functional data from formulas shown on Fig. 3, (ii) quantities from data inventory reported in table 1, and (iii) transport distances between source of materials and construction sites, authors developed the Overall Transport Cost Function at the level of buildings (Fig. 4). Afterwards, the distance breakeven point was calculated for each case study, taking as a relevant input, a maximum cost limit determined by the cost savings between LC3 and conventional cements. The economic distance threshold was anticipated around 50 km in the Forsa system, 141 km in the blocks building and 345 km for Grand panel. It means that beyond such a threshold the construction activities would become economically unfeasible, if transport parameters are taken into consideration.
However, it appears to be clear that both material selection and the construction technology choice have to be thought in the light of case-to-case building design/location, because depending on the distance from construction site to quarries — particularly the deposits of aggregates due to the enormous amount per concrete volume — the construction method might be subject to adaptations and rethinking.

4. Conclusions
According to the case studies taken from Villa Clara province (Cuba), the future implementation of LC3 within the construction sector would attain better eco-efficiency parameters if those building methods characterised by medium-to-high level of industrialisation are prioritised. Least industrial intensive choices — such as concrete blocks — seems to be highly correlated to cement consumption, in turn, meaning high energy consumption, carbon emissions and production costs. Transportation parameters also would strongly influence the material selection and eventually the construction technology choice. None of the construction techniques is, in principle, superior per se; a proper combination of them based on a multiple-criteria approach, let decision makers better stick to the suitable benchmark combination of techniques through the lens of sustainability.

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