EPiC Series in Built Environment

Volume 3, 2022, Pages 740–748

ASC2022. 58th Annual Associated Schools
of Construction International Conference

EPiC
Built
Environment

CO2eq Comparison Between a Light Gauge Steel Framing Structure and a CMU Structure for Single-Family Residential Projects in Costa Rica

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The challenges posed by the degradation of the planet's environment are of increasing importance. The United Nations have called for a substantial reduction of climate change pollutants such as carbon dioxide equivalents (CO2eq) within the next decade. The construction industry and building operations contribute an estimated 39% of the worldwide CO2eq, with 28% attributed to operational emissions and the remaining 11% to embodied emissions. This case study analyzes the embodied CO2eq by the structural portion of three residential construction projects in Costa Rica using two building systems. One building system is widely used locally, consisting of load-bearing concrete masonry unit walls and concrete elements. The other building system is a recently introduced alternative based on light gauge steel framing and paneling. The analysis shows that the light gauge steel frame alternative is more efficient in terms of embodied CO2eq by 33% averaging the three models which translates to 52.4 kgCO2eq saving per square meter of living space built. The research is limited to the three models examined, which were representative of low income, middle complexity, and higher-end types of local housing units. Construction time, cost, and other factors were not considered in this study.

Keywords: Embodied Carbon Dioxide Equivalent, Light Gauge Steel Framing, Concrete Masonry Construction, Costa Rica Construction Industry

Introduction

The degradation of the planet's environment is a subject of growing concern. One of the major causes of this is global warming, caused by the greenhouse effect resulting from the increasing volume of gases harmful to the environment generated by natural gases and by-products of human activities (Gopi, Senior, van de Lindt, Strong, & Valdes , 2015). These Green House Gases warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space. Global Warming Potential (GWP) is a concept developed to allow comparisons of the Global warming impacts of different gases. GWP is in itself a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period, usually 100 years, relative to the emissions of 1 ton of carbon dioxide (CO2) over the same period (United States Environmetal Protection Agency, n.d.). For practicality, CO2 equivalent emissions (CO2

T. Leathem, W. Collins and A. Perrenoud (eds.), ASC2022 (EPiC Series in Built Environment, vol. 3), pp. 740–748

emissions or CO2 eq) are used as a common unit of measure of GWP that considers CO2 and the combined effect of gases influencing the greenhouse effect (Athena Sustainable Materials Institute, 2019).

Building operation and construction are estimated to be responsible for 39% of CO2 emissions in the world, with 28% percent of this proportion being related to operations emissions necessary for the cooling, heating and power consumption of buildings, and 11% is due to the embodied CO2 emissions associated with materials and construction processes throughout the whole building lifecycle (World Green Building Council , 2020). An estimated 6% of the total emissions attributed to buildings and construction are considered direct, upfront CO2 emissions from materials and construction processes to build residential projects (UN Environment Programme, 2020). The United Nations is currently promoting that by 2030, all new buildings, infrastructure, and renovations will have at least 40% less embodied CO2, with significant upfront carbon reduction (United Nations Department of Economic and Social Affairs, 2015). Embodied construction CO2eq is defined as the amount of CO2eq released during the manufacturing, transportation, construction, and end-of-life phases of all building materials. Therefore, there is a need to focus on the key sources of embodied CO2, namely the structural elements such as foundations, frames, and other forms of superstructures, which often represent the most prominent contributors (UK Green Building Council, 2017). Sustainability performance in terms of GWP has been considered as influential as the traditional factors when choosing a structural system, namely code, cost, construction schedule, and site constraints (Griffin, Reed, & Hsu, 2006).

The construction industry in Costa Rica has had a recent long period of decelaration, accompanied by an increase in the cost of materials caused by international market pressures (Camara Costarricense de la Construccion (CCC), 2021). The fierce competition created by this environment has forced the market to open the doors to non traditional structural systems to compete with long standing traditional mainly concrete based systems. The objective of this study was to quantify and contrast the embodied CO2eq of two structural systems available in Costa Rica for three typical local residential housing designs. The relative competitiveness of each system was not considered in this study for factors other than their embodied CO2eq. Costa Rica's economy is strongly tied to its projection as a beacon of sustainability, and is internationally recognized as a pioneer nation that holds sustainability at its core of societal and economial policies (Government of Costa Rica , 2019), making the factors analyzed in this study relevant as part of the national vision for a sustainable future.

Literature Review

A case to use Carbon Dioxide equivalency as a sustainable criterion for Bridge design was made by performing a systematic assessment of the embodied CO2eq by the superstructures of trunkline bridges in the State of Colorado, U.S.A. and creating a sustainability ranking scale based CO2eq of each bridge, thus providing a simple approach to facilitate efficient decision making when choosing a design approach of similar systems (Gopi, Senior, van de Lindt, Strong, & Valdes , 2015). The study emphasizes on the need for sustainable construction and that sustainability criteria should play a significant role in such design decisions.

An analysis was done to compare the cost and embodied energy of the same house located in two different seismic zones built on masonry, with embodied anergy calculated by quantifying the materials in terms of weight and using the ICE database (Cobirzan, et al., 2017) The conclusion is that the embodied energy is lower in the house located in the low seismic zone in comparison to the house of same architectural distribution located in a high seismic zone, caused by the increased amount of concrete and reinforcement steel used in the latter. These results highlight the necessity of evaluating embodied energy at a design level to make sustainable design decisions, which becomes of higher importance in high seismic areas. For reference, the computed result of embodied CO2 found in this study for confined masonry is approximately 134 kgCO2 eq per square meter.

A life Cycle Environmental Assessment of Light Steel framed systems was done featuring cement-based walls and floors (Abouhamad & Abu-Hamd, 2020). The case study was a building built in Cairo University, used for administration occupancy, with a floor plan of 256 square meters and five floor of 3.5 meters in height. To calculate the embodied energy of the building the Athena Impact Estimator for Buildings was used. The author concludes that Light Steel Framing systems have lower embodied energy than conventional systems and that the construction system selection process taken early on in the design stage affect the expected environmental impacts of the building over its service life. For reference, the computed result for embodied CO2 including foundations, wall shells and steel framing was computed at 140 kgCO2eq / sqm.

Most of the literature reviewed analyses the embodied carbon of a building in one single system, but none was found to compare a same building using the two alternatives. This research contributes to the body of knowledge by analyzing different models in each alternative.

Structural System for Residential Construction in Costa Rica

The most common structural system for residential construction used in the country consists of load-bearing concrete masonry unit (CMU) walls and reinforced concrete foundations and slabs. However, this approach has been challenged in recent years by a light gauge steel framing and paneling system. The two structural systems analyzed in this investigation were the Light Gauge Steel Framing and the CMU System.

The light gauge steel framing system is manufactured from cold-formed steel and is emerging in the international markets as an innovative and cost-efficient solution, with its basic building elements being cold-formed C or U sections that are fabricated off-site into panels and then transported to the site ready for erection (Abouhamad & Abu-Hamd, 2020). Load-bearing walls consist of galvanized steel profiles designed to form structures complying with seismic regulations while providing cladding and interior wall face coverings. The foundation system considered for all cases consisted of concrete mat foundations. In addition, they included a reinforced concrete slab and additional reinforcement beneath the walls in the form of integrated strip footings.

The CMU system considered for this study consisted of structurally confined load bearing masonry. CMUs are installed and reinforced as required and then structurally confined with a network of onsite poured concrete beams and columns. Walls are supported by strip footing foundations that are independent of the concrete slab used for floors. Structural concrete elements such as beams, columns, and footing are poured with a minimum strength of 210 kg/cm^2.

Case Study Models

Three residential models were analyzed, varying in area and complexity. The most basic unit had an area of 42 m^2, one story, and a relatively high wall density. An intermediate model also had one story, but a higher area of 209 m^2, thicker walls, and larger living spaces. Finally, the most complex and higher income-oriented model had two stories and an area of 167 m^2, requiring a more elaborate and thicker structural system. The deliberate use of these models allowed a deeper observation of the behavior of the competing systems, as discussed later in this paper. All three models are located in Playas del Coco, in the Guanacaste province of Costa Rica. The location is relevant as this directly affects the results when using different tools and software to calculate embodied carbon of materials.

Figures 1 to 3 show the floor plans of each model, and Table 1 shows the details of the models used in the study

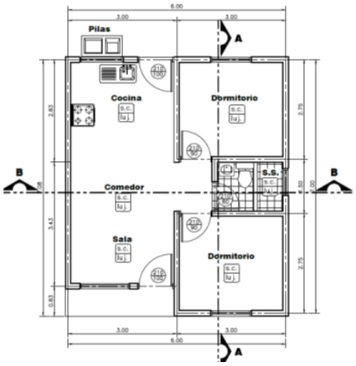

Figure 1. Floor plan low-income house model

Figure 2. Floor plan one story house model

Figure 3. Floor plan, two-story house model

Table 1

General Information for Case Studies

Model	Area (sqm)	Wall density (m^2 wall/m^2 floor)	Masonry System		Light Gauge Steel Framing System			
			Wall thickness	Strip foundation	Section Width	Gauge	Stud Spacing	Nog Spacing
Low-Income	42	2.65	12 cm	50 x 20 cm	3 ½”	22	60 cm	120 cm
One Story	209	1.49	15 cm	40 x 20 cm	3 ½”	18 and 20	40 cm	90 cm
Two Story	167	2.29	15 cm	60 x 20 cm	3 ½”	18 and 20	40 cm	90 cm

Methodology

This case study included the following steps:

1. Investigate previous research about the analyzed structural systems including other studies that use embodied carbon to determine their environmental performance.
2. Research the availability and capabilities of existing software tools and choose the most appropriate one for this investigation.
3. Quantify areas and volumes for each of the researched models.
4. Estimate the embodied CO2eq for each model in each of the two alternative systems.

Analyze the results.

Building components

Only differentiating elements were analyzed for each system; that is, common elements were not considered such as structure of second floor slabs which can be built using the same slab system in both systems, roof decking, roof cladding, finishes, electrical, mechanical, plumbing, heating, ventilation, and air conditioning systems Elements for the CMU system consisted of foundations, slabs on grade, confined masonry walls. For the light gauge steel framing system, elements were framing, including fiber glass insulation, fiber cement cladding, and regular gypsum walls for interior faces.

Variables and Software Input

Two software packages and databases were considered for this investigation. The Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2008) consists of a database developed in Bath, England, for embodied carbon in commonly used materials in construction. The second software package was the Impact Estimator Software published by the Athena Sustainable Materials Institute in Canada and the United States, which contains a wide variety of options to choose from when computing information both in generalities for the project and specific materials. While ICE has a limited selection in materials when choosing drywall and cladding, the Impact Estimator Software has a balanced array for selection in all materials needed for this calculation. In addition, the geographic location and weather characteristics for the Impact Estimator Software fit more to the Costa Rican conditions than the ICE. Another advantage of the Impact Estimator software package is that the results include a life cycle assessment comprising product stage, construction process stage, use stage, end of life stage, and benefits and loads beyond the Building Life Cycle stage. This information is relevant for the study as the alternatives analyzed consist of building components with different life spans and end-of-life benefits due to their recycling and reuse capabilities (Athena Sustainable Materials Institute, 2019). Therefore, the Impact Estimator Software was chosen as the main tool to estimate CO2eq quantities.

When using the Impact Estimator, the first step is to input general information, specifically important: a) life span of the structure: 50 years for model 1 and 70 years for models 2 and 3. b) location: Orlando, Florida for its similarities in weather characteristics in the area as compared to the location of the case study, and for its relative proximity to Costa Rica when compared to other locations available.

Table 2 shows the items included in the analysis when inputting specific material quantities into the software. For clarity and as an example, Tables 3 and 4 show the bill of materials used for each alternative on the low-income house model. The remaining models follow the same form.

Table 2

Structural Elements considered for the analysis

Item	**Description**	**Type analyzed**
1	Concrete for footings, floors, beams, and columns	ID436 Concrete Benchmark CAN 25 MPa.
2	Concrete to fill concrete blocks	ID435 Concrete Benchmark CAN 15 MPa.
3	Masonry walls, model 1	ID059 4-inch normal weight CMU
4	Masonry walls, models 2 and 3	ID389 6-inch normal weight CMU
5	Reinforcing Steel	ID024 Rebar, Rod, Light sections.
6	Light Gauge Steel Framing wall structure	ID031 Galvanized Studs.
7	Interior walls one face for Light Gauge Steel Framing Option	ID050 ½” Regular gypsum Boards
8	Insulation in all walls for Gauge Steel framing options	ID041 Fiber Glass Batt R11-15
9	Exterior cladding for Light Gauge Steel Framing Option	ID125 Fiber Cement

Table 3

Bill of materials for concrete alternative on low – income house model

Material	Unit	Total	Foundations	Walls	Mass Value	Mass Unit
4" Normal Weight CMU	Blocks	1047.64	0.00	1047.64	11.47	Tons
Concrete CAN 15 MPa	m3	3.11	1.04	2.07	7.12	Tons
Concrete CAN 25 MPa	m3	10.50	7.23	3.27	24.45	Tons
Mortar	m3	0.82	0.00	0.82	1.54	Tons
Rebar, Rod, Light Sections	Tons	0.74	0.32	0.43	0.74	Tons

Table 4
Bill of materials for light gauge steel framing alternative on low – income house model

Material	Unit	Total	Foundations	Walls	Mass Value	Mass Unit
1/2" Regular Gypsum Board	m2	169.60	0.00	169.60	1.37	Tons
Concrete CAN 25 MPa	m3	7.74	7.74	0.00	18.02	Tons
FG Batt R11-15	m2 (25mm)	111.30	0.00	111.30	0.03	Tons
Fiber Cement	m2	29.72	0.00	29.72	0.42	Tons
Galvanized Studs	Tons	0.55	0.00	0.55	0.55	Tons
Rebar, Rod, Light Sections	Tons	0.37	0.37	0.00	0.37	Tons

Results and Discussion

Table 5 summarizes the result of each model on each alternative system. The results were consistent with previous research, as discussed in this section, especially compared to the one-story model analyzed by Corbizan et al. and the two-story model studies by Aboumad & Abu-Hamd. The higher figure for the five-story building is also consistent with the fact that a multistory project will inherently have a more robust wall system and foundation than a typical single-family house. Tables 5 summarizes the quantities embodied for each analyzed structural system in each house model.

Table 5.
CO2 results for all models

Structural Masonry Option				**Light Gauge Steel Framing Option**			
Low- Income model							
Component	kgCO2eq	kgCO2eq/sqm	%	Component	KgCO2eq	KgCO2eq/sqm	%
Foundations	3130.00	74.52	42	Foundations	3060.00	72.86	68
Walls	4309.55	102.61	58	Walls	1431.07	34.07	58
Total	**7439.55**	**177.13**	**100**	**Total**	**4491.07**	**106.93**	**100**
One Story Model							
Component	kgCO2eq	kgCO2eq/m^2	%	Component	KgCO2eq	KgCO2eq/m^2	%
Foundations	12477.89	59.70	44	Foundations	12879.63	61.63	63
Walls	15793.07	75.56	56	Walls	7550.00	36.12	37
Total	**28270.96**	**135.27**	**100**	**Total**	**20429.62**	**97.75**	**100**
Two Story model							
Component	kgCO2eq	kgCO2eq/m^2	%	Component	KgCO2eq	KgCO2eq/m^2	%
Foundations	8499.62	50.90	32	Foundations	8059.98	48.26	44
Walls	18063.66	108.17	68	Walls	10242.89	61.33	56
Total	**26563.28**	**159.06**	**100**	**Total**	**18302.87**	**109.60**	**100**

The model with the biggest embodied CO2eq per square meter was the low-income housing unit. Probable factors for this result are the model's wall density and its structural system's useful life. Given that it is a compact design with a higher density of walls per square meter of floor, the total embodied CO2eq for the concrete block option for this model was 177 KgCO2eq/sqm, which is 12% higher than the average of the three models. In contrast, the lightweight gauge steel alternative had 106

KgCO2/sqm, only 2% above the three-model average. Moreover, the expected useful life of the low-income house model was estimated at 50 years, compared to 70 years for the larger one and two-story models (Organo de Normalizacion Tecnica, 2020). This difference in expected useful life influences the results. There is no need to replace any part of the structure in either of the two structural systems analyzed for the low-income unit. In contrast, the larger houses need to replace certain parts of the light gauge steel framing system between years 50 and 70, resulting in a more significant difference in KgCO2eq/sqm between the two structural systems for the two larger units. The results for total kgCO2eq per alternative per lifecycle stage can be seen in Figure 5.

Table 6 shows the average KgCO2/sqm for key structural elements across the three house models. The light gauge steel framing system performed better in every case considered. The average embodied energy per square meter of the light gauge steel framing alternative was computed at 104.75 $kgCO_2$/sqm, which is 33% less than the average concrete block house at 157.15 $kgCO_2$/sqm as the reference. The walls are the differentiators in the results found, as the difference in foundations is of only 1% as compared to the 54% difference found in walls.

Table 6

Average kgCO2eq/m^2 per alternative

Component	Concrete Block	Light Gauge Steel Framing	Difference %	Difference kgCO2/sqm
	KgCO2/m^2	GgCO2/m^2		
Foundations	61.7	60.9	-1%	-0.8
Walls	95.5	43.9	-54%	-51.6
Total	157.2	104.8	-33%	-52.4

Conclusion

In this case study project, located in the Guanacaste province of Costa Rica, three houses were compared in terms of kgCO2eq/sqm. The study focused on using two structural alternatives: the concrete block system, specifically confined masonry, widely used and a traditional way of building in the country, and the other an up-and-coming system in the local market, the light gauge steel framing system. Foundations, concrete slab on grade, and walls were compared by calculating the embodied carbon of one and the other. The light gauge steel framing system performs better in every case with a considerably lesser embodied CO2 per square meter than the concrete counterpart. In addition, four factors that directly affect the embodied carbon of each system were: a) wall thickness, b) density of walls, c) repairs and replacement of parts, and d) recycling and reusing potential. Foundations were not found to have a significant differentiating effect on the results.

The results found in this study are limited to single-family residential projects with similar floor plans and wall density as the three samples, built on a geographic location similar to Playas del Coco, Guanacaste in terms of weather and geographic location. However, the results found show a tendency worth exploring by adding more case studies with different characteristics to validate if the results found apply to other regions in terms of weather characteristics and seismic activity and other types of projects in terms of use and size.

Of particular importance are the results found on the low-income housing sample, as this floor plan is widely used and is the benchmark for this type of project in the country. Given this condition, the results apply to most low-income housing projects in Costa Rica, as all the regions are seismic and have similar weather conditions. In Costa Rica, low-income housing is state-sponsored and is built not in single units, taking advantage of the economy of scale by building several units at a time. Further research can analyze the cost and schedule factors of the two alternatives by using a multi-unit project as a case study to determine if the light gauge steel framing alternative is the better performer in terms of embodied carbon and be less costly and faster to build. If this is the case, this system might prove to be the most sustainable way of building state-sponsored low-income projects. Operations emissions were not considered in this study, which is an important factor that can be considered in determining the most alternative environmental overall in terms of CO2eq from operations and embodied emissions.

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