Integrated sustainable building design in the tropics: case study “Fabrica de Cultura”, Barranquilla, Colombia

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Abstract

This paper presents a case study of integrated sustainable building design in the tropics. In an interdisciplinary approach, we evaluated a series of strategies to increase the expected performance of a building prototype in the city of Barranquilla, Colombia. We created plausible architectural options, and used building performance simulation techniques to evaluate the feasibility of energy and water efficiency strategies. The aim was to develop close to optimal solutions to minimize the use of resources in the building while assuring high standards of comfort, an attractive return on investment, and an appealing architectural expression. As a result, four strategic bundles or sustainability concepts were seamlessly integrated into the architecture of the building. In comparison with a local school, the building achieves up to 93% of net energy savings and related emissions, 86% of water savings, and COP 144.5 million (USD 76,891.34) of yearly economic savings with a payback time period of 7.4 years. The results of this integrated approach successfully address the three pillars of sustainable development (i.e. social, economic and environmental) at the building scale and represent an exemplary case for the upcoming Colombian Green Building Code.
Keywords: sustainable building design in the tropics, energy and water efficiency in buildings, integrated and participatory building design.

1 Introduction

On-going social, economic and environmental changes have induced the renewal and expansion of the built environment with a focus in energy and water

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conservation [1]. In the tropics of Latin-American countries, high utility prices combined with an unreliable supply, represents a clear opportunity to foster energy and water efficiency strategies in buildings [2]. In this context, the promotion of integrated sustainable building design represents the key to holistic planning for maximum conservation of resources and improvement of living standards in buildings.

Integrated approaches in the field of sustainable building design aim at finding an intersection between architecture and sustainable building technologies (e.g. [2, 3]). This type of approach facilitates the translation of energy efficiency strategies into solutions in close relation with occupant needs and the building's architecture. In the Colombian tropics, integrated approaches of this sense are still in a premature stage as the need for sustainable buildings in the Colombian coast is a relatively new topic. In order to address this issue, the Colombian government is currently preparing a green building code with a specific version for the Caribbean coast [4].

We have identified a clear challenge in this setting for sustainable building design itself, which includes an increase in occupant comfort, architectural quality, and reliability of supply while simultaneously saving energy and water. With a relative humidity of 90%, and temperatures over 35°C, maintaining comfortable building conditions in cities on the Caribbean becomes a resource intensive operation. In addition, the scarcity of economic resources in this setting represents one of the biggest challenges as it might hinder the integration of sustainable design alternatives. What prototypical strategies and/or design guidelines can facilitate the sustainable development of the building stock in this setting at affordable costs?

Following this research question, we defined strategic bundles that optimise social, economic, and environmental values for a real case study in the Caribbean coast of Colombia. The case study "Fabrica de Cultura" consists of the construction of a new sustainable school of arts and music with a capacity of 1000 people and a size of 7000m^2 in the city centre of the city of Barranquilla.

The strategic bundles and concepts developed in this research project will not only contribute to the realization of this sustainable building prototype, but also will represent an exemplary case for the development of the Colombian Green Building Code with its specific version for the Caribbean coast.

In Section 2 we present an integrated methodology for the analysis and evaluation of energy and water efficiency strategies for different architectural options. In Section 3 we present the results in form of strategic bundles/concepts followed by a discussion and final conclusions in Section 4.

2 Methodology

Our approach for integrated sustainable building design involves the technical, environmental, and economical assessment of strategies in an interdisciplinary setting. The assessment is carried out in an iterative manner through a series of workshops with local stakeholders, architects, structural and building systems engineers. Figure 1 outlines our general methodological framework.

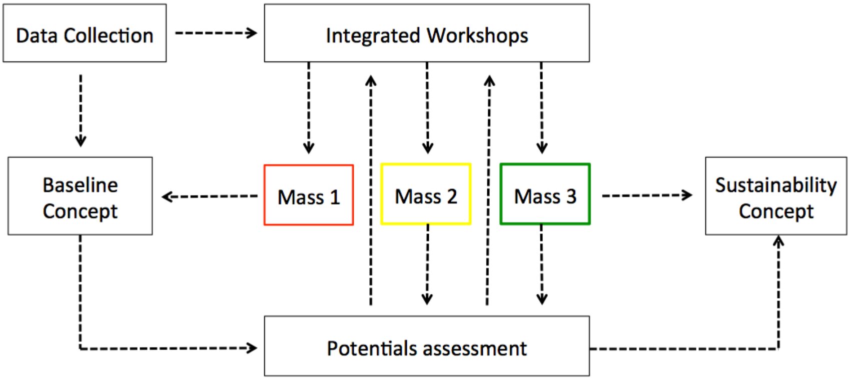


Figure 1: General methodological framework.

2.1 Data collection

We collected data regarding climate [5], energy and water consumption [6] and utility prices [7] applicable to an average school in the city of Barranquilla. In addition, we gathered data of construction practices, occupancy, and appliances-use through site visits and surveys to prospect users. Data about investment, operational and maintenance costs of potential energy and water efficiency strategies were determined from local construction companies [8] and list prices [9].

2.2 Baseline concept

From the data collected in Section 2.1, we set-up a baseline concept for further comparison purposes. The baseline concept is based on a local school in Barranquilla. Such a school consists of single glazed windows, single brick walls, no insulation, no shading devices, mini-split air-conditioning units, halogen lighting and a typical consumption of 120 kWh/m^2.a of electricity and 30 l.p.d of water. The cost of electricity is 312 COP/kWh [$0.15/kWh],

2.3 Concept development

As different strategies were analysed (see section 2.4), a series of integrated workshops with architects, engineers and local stakeholders enabled the iterative development of consecutive architectural concepts or masses (Figure 1). Each mass represents a milestone in the evolution of the building concept where Mass 1 was the first and Mass 3 was the final sustainable building solution.

2.4 Potentials analysis and assessment

Based on past research [10], we determined a set of plausible strategies or potentials to improve the performance of the baseline:

1. Building orientation;
2. Shading systems;
3. Natural lighting use;
4. Natural ventilation and building program distribution;
5. Building envelope improvement;
6. Use of energy and water efficiency equipment;
7. Energy efficient air-conditioning (A/C) for thermal comfort;
8. Decentralized energy production;
9. Rain water harvesting and grey water reuse.

In order to account for both positive and negative rebound effects of these strategies (e.g. natural lighting use to reduce artificial lighting but at a cost of higher solar gains and cooling loads), we used the real-time simulation tool Sefaira [11]. The tool allows simultaneously modelling, parameterizing, and comparing the effects of each strategy in the overall energy and water consumption, carbon footprint and operational costs of different architectural masses. During the analysis, we assumed strategies number 1–4 to not have an additional investment cost, as they are seamlessly integrated in the architectural composition of the building. For the rest of strategies we sized the type of components needed for their implementation and determined their costs based on the data collected in section 2.1.

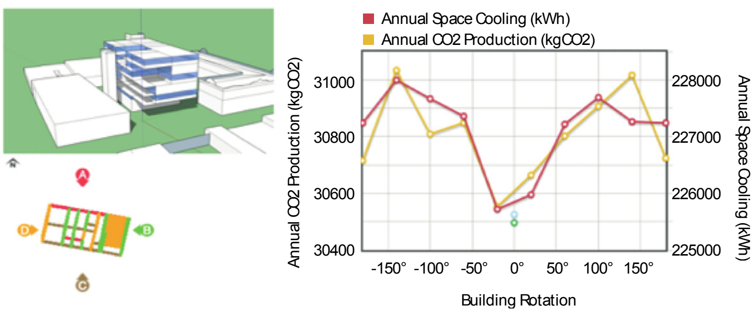


Figure 2: Parametric analysis of building orientation (Mass 2).

2.4.1 Building orientation

In the tropics, an optimal building orientation will attempt to reduce the amount of surface area exposed to the sun (west and east facades in our case) and increase that exposed to the prevailing wind direction (south-east in our case) [10]. As in Figure 2, this option was parameterized using Sefaira and agreed in the integrated workshops. The optimum solution maintained the buildings rectangular shape with a slight rotation to the southwest.

2.4.2 Shading systems

Horizontal shading systems were investigated in Sefaira by parameterizing the projected length of horizontal floor beyond the facade. In Figure 3, the annual cooling requirements decrease as the horizontal floor projection increases up to a settle point of around 1.7 m. As shown in Figures 4–5, we evaluated several forms of horizontal façade systems. The selected horizontal shading system of 2 m length doubles as an external corridor to enable the circulation of people around the building.

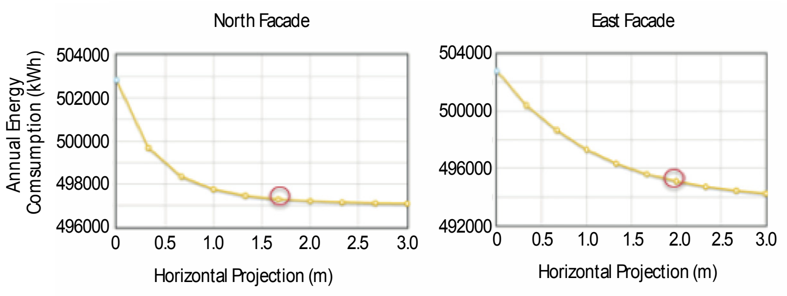


Figure 3: Parametric analysis of horizontal shading on North and East facades (Mass 2).

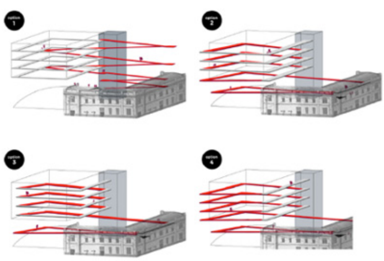


Figure 4: Circulation and shading studies by Urban-Think Tank ETHZ.

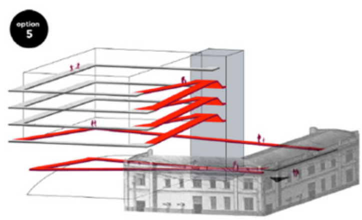


Figure 5: External corridor and shading device by Urban-Think Tank ETHZ.

2.4.3 Building envelope

The contribution to the yearly heat gain of the building due to thermal conduction is analysed for each component of the building envelope. Most of the conduction gains in the building occur through walls (57.1%), followed by the roof (19.4%), floor (12.8%), and windows (10.4%). We iteratively simulated the effect of reducing the thermal transmittance of every surface (U-Value) to the savings in the cooling energy demand. From the results and further discussions with architects and local manufacturers, plausible U-Values were selected (2.7 W/m^2.K for windows, 0.29 W/m^2.K for roofs, 0.81 W/m^2.K for floors, and 0.42 W/m^2.K for opaque facades).

2.4.4 Natural lighting use

For the analysis of natural light we assumed a target value of illuminance measured at desk level of at least 400 lux during 80% of daylight hours in the building [12]. In a series of integrated workshops we determined plausible configurations of window-wall ratios and vertical and horizontal openings that could help us to get as close as possible to this goal without affecting the efficiency of the building. As a result of both strategies we defined a 13.5x6.5m atrium in the centre of the building and a window to wall ratio of 30% to be maintained. A representation of the model used for this analysis is presented in Figure 6.

2.4.5 Natural ventilation and change in building program distribution

In order to decrease the use of mechanical ventilation we jointly evaluated the relocation of: a) activities with high internal gains (i.e. dancing rooms) to areas with low solar radiation (north and east facades); b) areas with low occupancy (i.e. workshops, corridors) to zones with natural cross-ventilation (i.e. close to atrium and orientated to south façade). These rooms will neither require A/C nor an insulated envelope thus reducing energy consumption. From this analysis 50% of the building can be naturally ventilated at 70% of comfort standard (i.e. 70% of occupied hours at 50% of relative humidity and a temperature of 24±1°C).

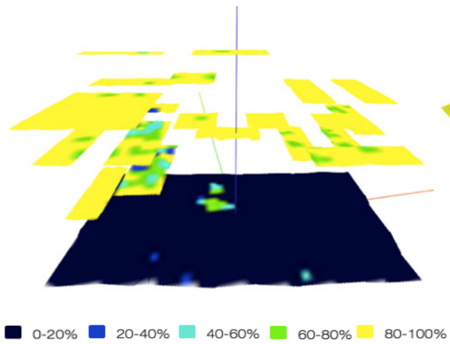
2.4.6 Energy and water saving appliances

Using Sefaira, we analysed the effects on electricity consumption switching from halogen to LED technology respectively considering a power density of 12W/m^2 and 3W/m^2 and standard properties related to illuminance and service life. Similarly, we analysed the effects of switching from mini-split units to a highly efficient central air-conditioning system with a seasonal COP of 3.4.

On the other hand, we analysed the effects on water consumption from the use of water saving fixtures such as water saving toilets (3 l/flush instead of 6 l/flush) and faucets (2 l/min instead of 8 l/min).

2.4.7 Decentralized energy production

We used Ecotect to calculate the solar insolation on all building surfaces (Figure 7). The average yearly solar radiation on the roof terrace (1687 kWh/m^2.a) makes photovoltaic (PV) electricity production an attractive option for the site. We used the performance of a grid-connected PV tool [13] to analyze diverse configurations and technologies of PV modules: free-standing, building integrated, mono-crystalline panels, poly-crystalline panels, CdTe and amorphous silicon. Out of the analysis, freestanding mono-crystalline modules were selected due to their high-energy yield, accessibility, and competitive price.



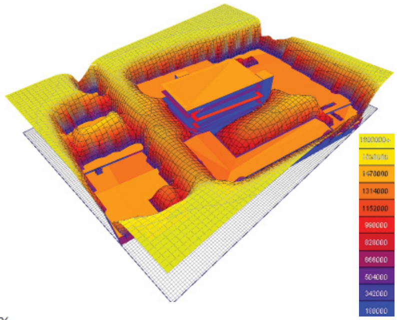


Figure 6: Day-lighting analysis after optimization (Mass 2).

Figure 7: Solar insolation analysis in $kWh/m^2.a$ (Mass 2).

The solar panels at their optimal orientation (1°) and slope (13°) could increase the solar yield of the installation in close to 15% relative to horizontal orientation. It does so at a cost to the total surface area available in 40% as the required array separation is high (73cm). The same stands in the case of a combination of PV technology with green roof. In principle the combination increases the efficiency of the PV installation by 6% and reduces the rainwater run-off by 50% [14], still requiring the same array spacing. Taking into account the low prices of mono-Si installation in the Colombian market, we considered an installation of a full field in the roof to generate more energy and be more profitable in the long run. The solar installation would have a yield of 152MWh of electricity per year including a surplus of 56MWh.

2.4.8 Rainwater harvesting and water reuse

Rainwater, which is in abundance between May and November [5], can be used for irrigation, and WC flushing. Following the approach of [15], we calculated the optimal catchment area and storage size of the system and included the results in Sefaira. Our results show that 17% of water savings could be obtained with a tank of $30m^3$ in size. In cities such as Barranquilla the lack of appropriate storm water distribution systems results in urban floods [16]. A rainwater harvesting system can provide a buffer during the heavy storms of October. This element forms part of what is considered a strategy for adaptation to climate change.

Water used for washing basins (grey water) can also be harvested and reused for water closet (WC) flushing. All the installations of potable water located outside of the restrooms are not considered inside the analysis. Their wastewater quality is too low (mix of oil, paint, corrosive liquids etc.) to provide an effective waste recovery system. We simulated the collection of grey water in the building with Sefaira and obtained potential savings of up to 60% of the annual water consumption. The costs of such installation are calculated according to [17, 18].

3 Results and discussion

From the previous analysis, we elaborated four strategic bundles for the efficient use of resources in the building Fabrica de Cultura. Each bundle has a two-fold sustainable approach: The first two (Figure 8(a)–(b)), aim at mitigating the environmental impact of buildings with energy conservation strategies. The rest (Figure 8(c)–(d)) aim at increasing the resilience of buildings to climate change through decentralized options of energy and water production.

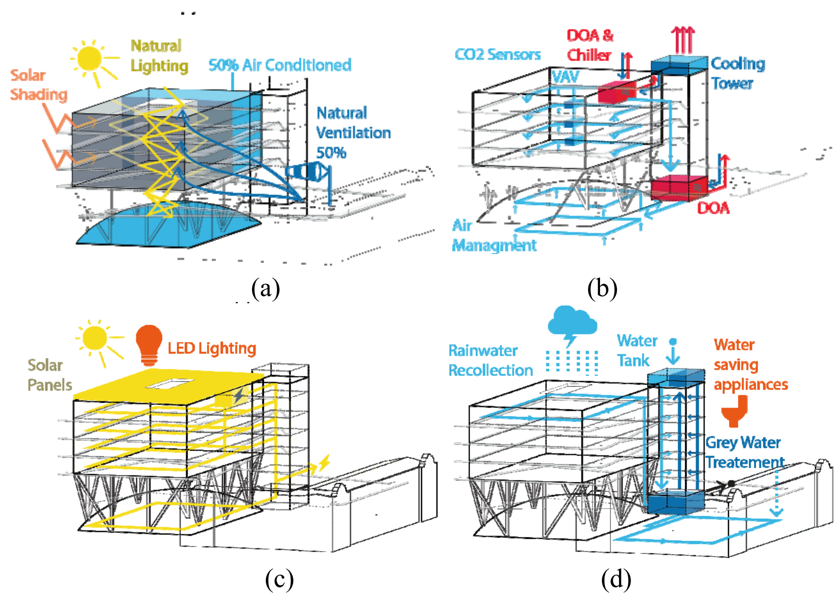


Figure 8: Sustainability building concepts/strategic bundles, (a) Natural ventilation and daylight use; (b) A/C and building envelope; (c) Decentralized energy production and artificial lighting; (d) Water management and reuse by Urban-Think Tank ETHZ.

3.1 Investment costs and estimated savings

In Table 1 we present a breakdown of the added costs and estimated savings per strategic bundle. For this, we considered the feed-in tariff from PV to be equal to two thirds of the local electricity price (i.e. 200 COP/kWh [$0.10/kWh]) in the worst-case scenario. With those strategic boundless, the Fabrica de Cultura could achieve up to 93% of net energy savings and related emissions, 86% of water savings and COP 144.5 million (USD 76,891.34) of economic savings. The added investment cost of the technologies would amount to COP 757 million or approximately 8% of the building construction costs.

Table 1: Estimated costs and net savings of various bundles/concepts*.

Bundle	Net energy/water Savings	Net annual utility savings in COP (USD)	Net annual CO_2 savings in ton/a	Added costs in COP (USD)
HVAC and building envelope	112MWh ↓25%	38’067.108 (19.351)	13.06	310’395.938 (155’198)
Decentralized power and artificial lighting	197MWh ↓44%*	51’205.488* (27.247)	22.89	406’799.128 (203.399)
Natural ventilation and day lighting	111MWh ↓24%	36’326.942 (19.331)	12.7	0
Water management and reuse	8648m^3 ↓86%	18’636.440 (9.917)	0	39’705.425 (19.852)

*This analysis considers all the energy generated from renewable energy sources on site (approximately 56MWh is exported).

3.2 Discounted payback period

We calculated the discounted payback time period per bundle strategy and in total. As in Figure 9 the return of investment of different energy or water efficiency strategies ranges from 1.5 to 16 years when implemented separately.

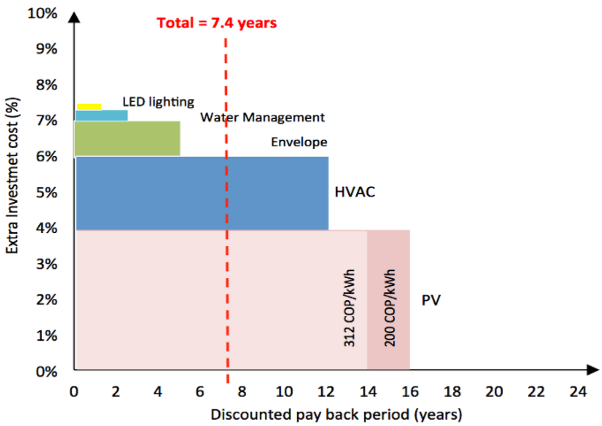


Figure 9: Discounted payback period (d=4.75%). Note that the payback period of the PV depends on the proposed feed in tariff rate.

When considering the implementation of all strategies in the worst-case scenario of feed-in tariff, the payback time of the whole investment costs with a discount rate of d=4.75% [19] is 7.4 years. With a feed-in-tariff equal to the grid price (312 COP/kWh [$0.15/kWh]) the payback time would furthermore reduce to 6.9 years. In a hypothetical environment of high inflation (d=12%) the total payback of investment is still reasonable, at 11.2 years.

3.3 Building performance

The "Fabrica de Cultura" has the potential to consume close to 50% less energy in comparison to a local school while still attaining much higher standards of comfort. Including on site generation, the net energy savings are 93%.

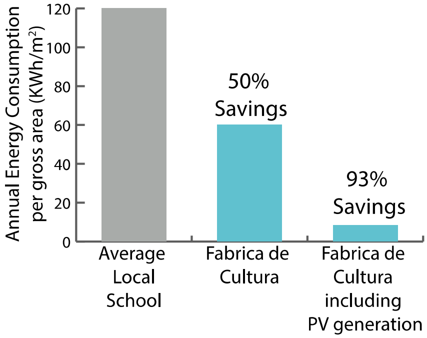


Figure 10: Comparison of local energy consumption and Fabrica de Cultura

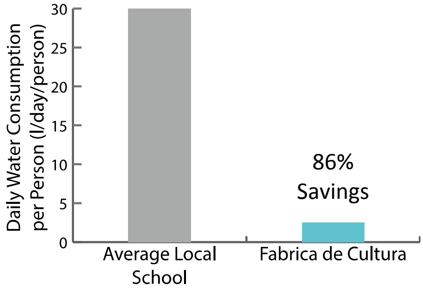


Figure 11: Comparison of local water consumption and Fabrica de Cultura.

3.4 Architectural integration

Our concept integrates into architecture an external service core and a circular ramp, which connects the auditorium and the school with a standing structure on the north.

Figure 12: Visualization of final sustainable building design by Urban-Think Tank ETHZ.

In cooperation with the design team, we have created a service core as the infrastructural backbone of the Fabrica de Cultura. It hosts all internal installations, bathrooms, main staircases, a service lift and the systems for recollection and treatment of rainwater and grey water. The main vertical ducting and piping for water supply, drainage, chilled water, telecommunications, and electricity are located in this structure.

4 Conclusions

Our integrated approach for sustainable building design facilitated the exploitation of synergies between the building's architecture and its infrastructure. The constant feedback to designers and the inclusion of local stakeholders in the process allowed us to find optimal solutions in a relatively short time. These set of solutions assure maximum sustainability and contribute to the mitigation and adaptation of urban areas to climate change. On a broader scale, these strategies could, in principle, be applied in similar cases throughout the tropics of Latin-American countries.

The final sustainability concept of the Fabrica de Cultura has the potential to consume close to 50% less energy and 86% less water in comparison with a local school in Barranquilla. This is achieved through the use of smart sensoring systems for air conditioning and day lighting, energy and water efficient devices and building components, and systems for recollection and treatment of rainwater and grey water. Furthermore, the building features a pioneer installation of photovoltaic panels (the biggest one so far in a Colombian urban area), which is then capable of bringing the total energy savings to 93%. All additional sustainability investment costs add up to just 8% of total building costs making it an economically pleasing alternative.

Considering a life expectancy of at least 50 years, these annual savings could in principle pay-off all the construction costs of the building, but more importantly, they could be reinvested in both maintenance and equipment (i.e. instruments, appliances etc.) necessary for the school.

In essence, the Fabrica de Cultura will be the first of its kind in a tropical Latin-American environment, and will become an exemplary case for the upcoming Colombian Green Building Code.

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