Bottom-up model for the sustainability assessment of rooftop-farming technologies. The case of Quito, Ecuador

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ABSTRACT:

Rooftop-farming technologies can transform unexploited roofs into agricultural areas; and though sstudies have theorised their potentials and constraints, their sustainability has not been quantified. Sustainability is a multidisciplinary concept involving different scales and study-fields. Therefore, the proposed bottom-up model quantifies the sustainability of implementing rooftop-farm technologies in building stocks using multi-criteria data on the economic, environmental, social and technological pillars from the city to the technology scale. This model handles large building samples as it is the first to combine Statistical Mining Techniques with the Integrated Value Model for Sustainability Assessment and simplified Life-Cycle Analysis. It has three consecutive stages. In the *City Stage* reference buildings are identified from the stock, the *Building Information Stage* determines the logistics and infrastructure requirements; and, the *Farm Technology Stage* quantifies the technologies sustainability. This model was used to assess the sustainability of three rooftop-farms (edible-green roofs, rooftop greenhouses and integrated rooftop greenhouses) on the educational stock in Quito, Ecuador. Two reference buildings accurately represented the city stock; and, in both typologies, edible-green rooftop farming technology obtained the highest sustainability index values of 0.62 and 0.65. The environmental pillar is the most discriminant in which green-roofs achieved twice the sustainability values for the rooftop-greenhouses due to their larger rainwater harvesting capacity, thermal resistance and contribution to the increment of urban greenspaces. This model permitted an objective comparison between the alternatives and identified the weak points in each technology.

Keywords: urban agriculture; clustering; reference buildings; sustainability assessment; school buildings

1. Introduction:

Urban rooftop farming (URF) can transform unexploited roofs into agricultural areas thus increasing the city food self-sufficiency (Buehler and Junge, 2016), reducing its environmental footprint (Viljoen and Bohn, 2014), and enhancing its social cohesion (Thomaier et al., 2014). Current studies dealing with the environmental performance of rooftop-farming -namely rooftop greenhouses (RTG) (Sanyé-Mengual et al., 2015a), integrated rooftop greenhouses (iRTG) (Sanjuan-Delmás et al., 2018), and green roofs (eGR) (Vacek et al., 2017) - quantify the impacts by these rooftop farms but disregard their symbiosis with their host-buildings. On the other hand, some studies consider the host-building constraints to quantify the urban food production potential -like the city wide study conducted in Boston, USA (Saha and Eckelman, 2017) or the study in a neighbourhood in Quito, Ecuador (Nadal et al., 2019) - but do not consider the sustainability or adequacy of these farms. Appendix A includes a complete list of the abbreviations used in this paper.

To date, most studies quantify the environmental and economic dimensions of URF, whereas the literature on social, governance, educational and technological aspects are limited (Sanyé-Mengual et al., 2018). Some studies had begun comparing URF to their ground counterparts, but no special attention has been giving to the comparison among URF technologies (Kim et al., 2018). What is more, quantitative data is lacking regarding the viability of rooftop-farming in large-scale applications (Haberman et al., 2014). Therefore, there is a need for a holistic sustainability model to strategically compare rooftop-farming alternatives and their implementation in a building stock, by dealing with multi-criteria indicators to characterize and monitor these technologies. As literature suggests (Artmann and Sartison, 2018), a bottom-up urban-modelling strategy is adequate for urban agriculture purposes. Bottom-up modelling analyses individual buildings in detail and then extrapolates these results to a city scale using statistical techniques (Li et al., 2018). One of these techniques is the use of mining tools to identify reference buildings that act as accurate representatives of the stock.

In this line, the objectives of this article are first to provide decision-makers with a new model for the sustainability evaluation of rooftop-farming dealing with quantitative and qualitative aspects; and then, to apply this model to compare rooftop-farming technologies on their suitability for addressing the main deficiencies of the existing school stock in Quito, Ecuador -mainly lack of greenspaces and roof's degradation. This model is the first to combine statistical mining with the Integrated Value

Model for Sustainability Assessment (*MIVES*) -a validated multi-criteria decision-making tool (Viñolas et al., 2009) and simplified life-cycle analysis (Zabalza Bribián et al., 2009). This article has six sections: a) the introduction and a brief state of the art on sustainability assessment of URF, b) the description of the new evaluation model, c) the presentation of the case study, d) the results, and e) the discussion of the model strengths and uncertainties, and f) the conclusions and future work.

1.1 A brief state of the art:

Recently, studies started comparing the sustainability of high-tech controlled-environment agriculture to open-air farming technologies. A cost-benefit analysis on the sustainability of edible-green roofs (*eGR*), RTGs and climate-controlled RTGs showed a non-viability for greenhouses due to high investments costs (Benis et al., 2018). Eaves (2018) compared the profitability of RTGs and vertical farms using simulation-based models and identified the inability of economically quantifying the co-benefits of the farms. Two building-based farms, eGR and RTG, and four ground-farms in the USA were assessed in Goldstein (2016) using life-cycle analysis *(LCA)*. That study showed that low-tech technologies have a better performance due to lower energy demand; however, the different crops and harvesting seasons complicated the comparison. Another study assessed the environmental impacts of three URF growing systems in Bologna, Italy using LCA and life-cycle costings *(LCC)* on prototype crops (Sanyé-Mengual et al., 2015b). The results highlighted the negative influence of water pumps in hydroponic crops; although, the limitations of those prototypes could have biased the correct allocation of resources in the life-cycle inventories.

The sustainability of URF has also been assessed using participatory methods to define sets of indicators, either to define their level of social acceptance (Specht et al., 2016), or to evaluate governance and planning policies (Landert et al., 2017). These studies highlight the need to select URF technologies appropriately to each context. A first simulation-based decision-making tool compared RTGs and two models of vertical farms using three indicators –water use, energy use, and food yield- (Benis et al., 2017), however qualitative and social aspects were not considered. Another study combined interviews with LCA and LCC to compare two types of green roofs (Kim et al., 2018). The interviews showed a preference for the edible-green roofs despite them having twice the life-cycle costs of the standard green roofs. However, this preference was not included in the sustainability quantification. A three-step scheme was formulated in Artmann and Sartison (2018), it first defines the farm's purpose, then assesses its implementation efficiency, and finally analyzes the three-folded sustainability of the farm. This scheme, to the best of the authors' knowledge, has not been applied to a real sample. Table 1 shows the available studies that compare the sustainability of two or more URF technologies classified according to the anaylisis point-of-view.

Table 1. Studies comparing the sustainability of URF technologies. Farm technologies, methods and indicators used.

Ref.	**Location**	**Method**	**Indicators**	**Technology**
Focus in economic parameters				
(Benis et al., 2018)	Lisbon, Portugal	Cost-benefit analysis	NPV, IRR, Payback period	eGR, RTG, RTG(c)
(Eaves and Eaves, 2018)	Quebec, Canada	Cost analysis	Gross profit	RTG, VF
Focus in environmental parameters				
(Goldstein et al., 2016)	Boston & NYC, USA	LCA	GWP Freshwater Ecotoxicity Marine eutrophication Water depletion Land use Resource depletion	RTG, eGR
(Sanyé-Mengual et al., 2015b)	Bologna, Italy	LCA LCC	GWP, Water depletion CED, Human toxicity Total cost	NFT, floating, soil beds
Focus in social parameters				
(Specht et al., 2016)	Berlin, Germany	Interviews	19 perceived benefits 24 perceived risks	
(Sanyé-Mengual et al., 2018)	Bologna, Italy	Participatory design	92 indicators	
(Landert et al., 2017)	Basel, Switzerland	Interviews	97 indicators	
Focus in holistic parameters				
(Kim et al., 2018)	Seoul, Korea	LCA / LCC / Interviews	Cumulative cost Environmental indicators	eGR, GR
(Artmann and Sartison, 2018)	Theoretical	3 step scheme: Purpose – Implementation efficiency – Impact efficiency	Production Regulatory services Cultural services	
(Fargue-Lelièvre and Clérino, 2018)	France	4-step tool: Objectives – Indicators –Parameters of interpretation / Auto-evaluation	7 objectives 30 indicators	

Llife-cycle assessment (LCA), life-cycle costs (LCC), geographic information systems (GIS), global warming potential (GWP), cumulative energy demand (CED), net present value (NPV), internal return rate (IRR), rooftop greenhouse (RTG), climate controlled rooftop greenhouse (RTG(c)), communal rooftop garden (cRG), private rooftop garden (pRG), open air farm (OAF), indoor farm (IF), vertical farm (VF), nutrient film technique (NFT), indoor vertical farm (iVF).

2. Methods:

The new sustainability evaluation model to compare rooftop-farming alternatives and its implementation in a building stock is presented in Figure 1 and includes three stages: a) City, b) Building Information, and c) Farming Technology. The conceptual scheme in Artmann (2018) served as the basis for the model. Various techniques and methods are used in each stage as to move a step foward compared to the models found in literature. In the City stage, statistical mining techniques serve to identify reference buildings from the building stock. The second stage combines fieldwork, simulation and literature review to analyse the technical feasibility of the roofs to host farms. The Farming Technology stage defines a sustainability valuation tool using the validated Integrated Value Model for Sustainability Assessment (MIVES) paired with a simplified LCA.

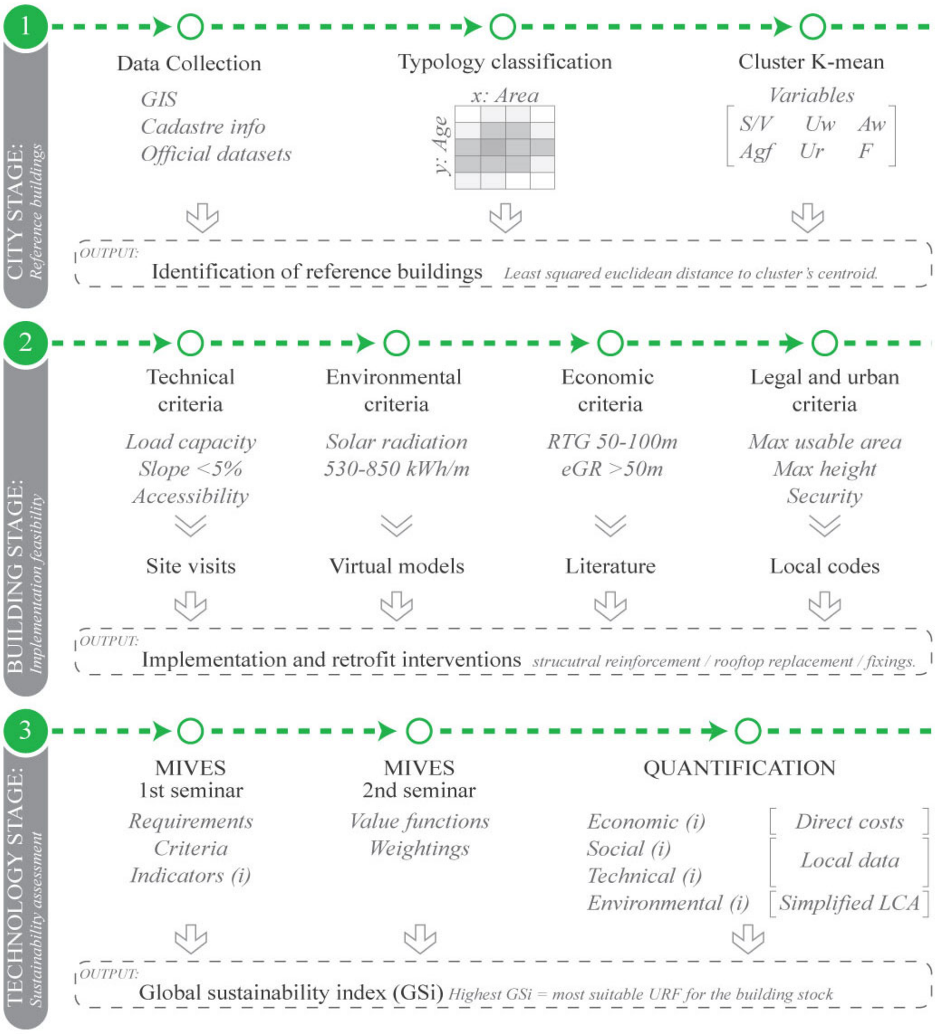


Figure 1. Stages, methods and studied parameters of the proposed assessment tool. Compactness (S/V), ground floor area (Agf), external wall area (Aw), U-value for walls (Uw), U-value for roofs (Ur), number of storeys (F), rooftop greenhouse (RTG), edible-green roof (eGR).

2.1 City Stage: Identification of reference buildings

A bottom-up urban-modelling strategy was used to permit the up-scaling of results at the city level. The school building stock was classified into architectural typologies as to obtain an in-depth knowledge of the current state of these buildings, and to identify the city-scale deficiencies. Researchers further evaluated the rooftop farming potential and its food self-sufficiency capacity. The methodology for the European project TABULA was used (Ballarini et al., 2014). It divides the edifices into categories defined by the construction period and gross floor area of the buildings; and then, identifies *reference buildings (*RBs*)* for each representative category (above 4%) using statistical *clustering K-mean method*. The subdivisions for the classification are steps of 1000 m^2 for gross floor area; and, milestones for economic or political relevant events and changes in construction codes for the construction period (Crespo and Ortiz, 1999).

Clustering is a data mining technique for finding subgroups with higher intra-cohesion than that of the entire sample. K-means method creates "k" non-overlapping clusters –each building belongs to only one cluster- represented by their centroids. As mining techniques are exploratory, the results are highly dependent on the data variables selected. A study found that a combination of six data variables provides the best cohesion results when using the k-mean method for building classification (Arambula Lara et al., 2014). Based on the classification of Italian schools (Arambula Lara et al., 2015) and Serbian schools (University of Belgrade, 2018), the independent variables chosen were: compactness (S/V), ground floor area (Agf), external wall area (Aw), U-value of walls (Uw), U-value of roofs (Ur) and, number of storeys (F).

The clustering algorithm was run in *R software* using libraries "*cclust", "cluster"* and "*vegan"*. First, the data variables were normalised to Z-scores due to the different measuring units; next, the presence of multivariate outliers –considered anomalous observations- was checked using the cumulative probability in a chi-square distribution of the Mahalanobis distance. Probabilities below 0.005 were considered outliers and discarded from the sample. The highest Calinski-Harabasz index served to identify the best number of “k” clusters. This index was calculated for k=2, k=3, k=4 and k=5. Once the number of “k” was defined, the k-mean algorithm was iterated until results converged. The clusters centroids are the mean values of the data variables for each subgroup. Their statistical significance was verified using the ANOVA test in *IBM SPSS Statistics*. Finally, the edifices with the least squared Euclidean distance to their cluster’s centroid were selected as reference buildings.

2.2 Building Information Stage: Implementation feasibility

The reference buildings are then analysed on account of their technical feasibility for hosting rooftop-farms. Based on the indicators used for studying the potential of rooftop-greenhouses in educational buildings (Nadal et al., 2018) and in retail parks (Sanyé-Mengual et al., 2016), the defined set of criteria are described below. Field visits to the RBs served for verifying its compliance. The associated reconstruction/adaptation costs are analysed as part of the sustainability valuation and not as pre-conditions for the implementation feasibility.

***Economic criteria**:* The usable roof area has to be free of all mechanical fixings and obstacles. For economic viability, greenhouses are limited to 50-100 m^2 in social uptakes and 500 m^2 for commercial purposes (Nadal et al., 2018). The minimum set area for other URFs was 50 m^2.

Environmental criteria: agriculture production requires a minimum solar radiation of 530-830 kWh/m^2/year (Nadal et al., 2018). The incident solar radiation was calculated on georeferenced 3D models of the RBs using *Insight-360.* These models include shadowing effects of the urban surroundings.

***Legal and urban criteria**:* requirements and constraints defined by local planning, construction and urban codes including floor-to-area ratios, maximum usable area, maximum building height, permitted land use and minimum fire and security measures.

Technical criteria: the roofs must have a minimum load capacity of 200 kg/m^2 and 489 kg/m^2 for communal rooftops and green roofs, respectively (Ministerio de Desarrollo Urbano y Vivienda, 2014). Rooftops must be flat (slope <5%) and accessible through staircases. The use of ladders and hatches is prohibited. Buildings that do not meet these criteria will require retrofit interventions like structural reinforcement or roof replacement.

2.3 Farming Technology Stage: Sustainability assessment

The sustainability evaluation uses the Integrated Value Model for Sustainable Assessment (*MIVES*), a multi-criteria decision-making method based on the multi-attribute utility theory. Viñolas (2009) provides a detailed description of this method. MIVES main advantages are its adaptability, specificity, and the inclusion of multiple data inputs. The crucial points contained in this method are the definition of a requirements tree and the use of value functions to compare indicators with different measurement units. The requirements tree is a hierarchical structure encompassing all aspects to be considered in the decision-making process. It is composed of requirements (R_k) subdivided into criteria (C_k) and these into indicators (I_k). Ten stakeholders from the municipality and construction, engineering and urban agriculture fields defined this tree during two seminars held in June 2018. This tree included only the most significant indicators to permit an efficient application of the model (Viñolas et al., 2009). This tree weights result from comparing the aspects inside each ramification and grading them based on their importance to the decision-making process. During the seminars, experts decided the weights based on proper knowledge and related bibliography. An Analytic Hierarchy Process (AHP) (Saaty, 1990) was used to allocate the final weights.

The requirements tree is valued sequentially starting from the direct quantification for the indicators and the application of the value functions. As previously said, value functions serve to compare indicators with different measurement units based on a 0 to 1 satisfaction scale. Five parameters define the value functions: indicator's maximum value (X_{max}), indicator's minimum value (X_{min}), indicator's value in the inflexion point (C_i), the non-dimensional value in the inflexion point (K_i), and the shape factor (P_i). The shape factor defines the function type (Viñolas et al., 2009). This parameter was assigned as follows: costs are linear functions (P_i=1), indicators with acceptable ranges are concave (P_i<1), and indicators with minimum mandatory requirements are convex (P_i>1). The minimum value for all indicators was zero, and the maximum was the highest of the alternatives. The criteria quantification is the sum of the indicators values multiplied by their weights. Similarly, the requirements and global sustainability values result from adding the non-dimensional values for their respective components scaled according to their weights.

Simplified LCAs were calculated for the construction and agriculture production phase of the rooftop-farms. These simplified LCAs include the following stages: production (extraction and manufacture), construction and transport, use, and end of life. The life-cycle inventories (*LCI*) were compiled from available published information and adapted to context considering manufacture locations, transport distances, transport types, electricity mix, and agricultural data. The simplified LCAs used a cut-off perspective in which waste practices were excluded for all materials as these are considered inputs for future processes, and the extraction stage is excluded for recycled materials. The transport to landfills or recycling plants was included. The lifespan for the URFs was set to 50 years, and thus, the LCIs include maintenance and material replacements. The LCA quantification was done on *SimaPro software* using the *EcoInvent database.*

3. Case Study:

Quito, the capital of Ecuador, has an equatorial highland climate with an average year-round temperature of 16°C and a daily thermal amplitude of 17 °C (Instituto Nacional de Meteorología e Hidrología, 2013). Quito is one of the first cities in South America to support urban agriculture and has one of the most active programs in the region (Agencia Metropolitana de Promoción Económica, 2005; Food and Agriculture Organization of the United Nations, 2014). However, land planning policies do not consider urban agriculture in their regulatory frameworks; and as such, there are no guidelines on urban-farming implementation nor the suitability of URF alternatives. Due to the educational and social benefits of rooftop farms, schools are prime locations for URF implementation (Nadal et al., 2018). The Ecuadorian Ministry of Education supports the creation of urban-farms in its schools, and in 2017 launched the "TiNi initiative" to provide half square meter of farmland for each student (Ministerio de Educación del Ecuador, 2016). Regrettably, ground space availability limited the creation of farms to peri-urban and rural schools.

School buildings in the city are mostly uninsulated concrete frame structures with single-layer envelopes made of medium-weight concrete blocks or bricks; the roofs are ribbed slabs or metal claddings (Escuela Politécnica Nacional, 1995). The building´s envelope is usually left unfinished, causing faster degradation and water infiltration through roof-wall joints. Most open spaces are cement courtyards, which is why less than a third of schools have green areas. Refurbishing the roofs to include rooftop-farms could address these deficiencies due to the co-benefits of URF, including increased thermal insulation, waterproofing, and larger life-spans. Additionally, URF could provide the required farm-space for the implementation of the TiNi initiative in urban schools.

3.1 Selection of rooftop farm technologies:

The most common rooftop farm used in social uptakes is soil-base open-air farming (*OAF*) due to its simpler management and implementation (Buehler and Junge, 2016). Several schools have used green-roof technology to create edible-green roofs (*eGR*). In 2010, a New York City public school constructed the first fully-equipped outdoor classroom on a green roof (Greenwich Village School, 2012). More recently, the Fifth-Street-Farm project created modular eGRs for use in NYC schools (Fifth Street Farm Project, 2008); sprouting similar initiatives across the USA and Canada (Fickes, 2014). Rooftop greenhouses (*RTG*) have also been created in educational buildings to serve as workshops and science labs (Sanyé-Mengual et al., 2014). In 2011, the New York Sun Works installed a RTG on the Manhattan School for Children (New York Sun Works, 2010). Following its success, the NYC

Department of Education installed 67 RTGs as part of its "Greenhouse Project" (Nordgrén, 2017), and Detroit installed RTGs in over a third of its public schools (Detroit Public Schools Community District, 2012). In line with the existent projects, the URF technologies assessed in this article are described below (see Figure 2). Appendix B provides construction details for these technologies.

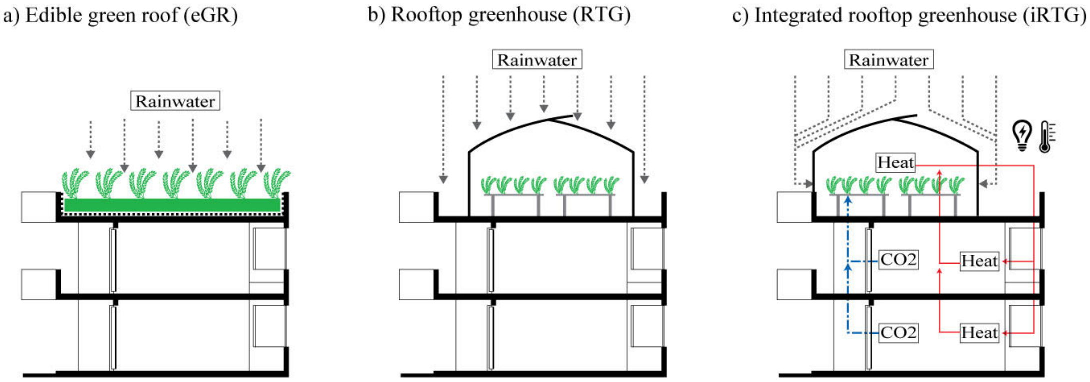


Figure 2. Rooftop farming technologies considered in the feasibility and sustainability assessment

Edible green roofs (eGR): agriculture is a relatively new application for green roofs, adding vegetable production to their known benefits of rainwater runoff reduction, energy conservation and mitigation of the heat island effect (Walters and Stoelzle Midden, 2018). Extensive green roofs (<15 cm depth) are adequate for shallow-root crops with low-yields; however, thicker substrates can achieve yields comparable to those of ground agriculture (Whittinghill et al., 2013). This study uses a semi-intensive roof with 20 cm substrate composed of expanded clay (60%), slag (10%), brick shards (10%), peat (10%) and organic compost (10%) as suggested in the literature (Vacek et al., 2017).

Rooftop greenhouse (RTG): The model used is an asymmetric-tropical vault with overhead ventilation, structural bolted frame and tensioners of galvanised steel, low-density polyethene (*LDPE*) enclosure and a polyester climate screen. This model is the most commonly used in the country (González, 2018). The hydroponic system is a modified Nutrient Film Technique (mNFT) in 4 inch PVC pipes, as suggested by the Ecuadorian Ministry of Agriculture (2018). The plants are grown in small baskets placed in the PVC channels where an electrical pump continuously recirculates the nutrient solution.

Integrated rooftop greenhouse (iRTG): this greenhouse exchanges metabolic flows -heat, CO_2 and water- with its host building as to reduce their aggregated environmental impact (Nadal et al., 2017). This greenhouse usually includes special features such as waste heat capture, rainwater harvesting, evaporative cooling and some form of renewable energy (Gould and Caplow, 2012). In this study, the iRTG uses the same model as the RTG and includes rainwater harvesting and a mechanical ventilation system; the analysis includes all construction interventions required to achieve an integrated RTG-building.

Year-round lettuce production served for accounting the resource consumption and yields achieved by each URF technology (see Table 2). Lettuce was selected as it is representative of the Ecuadorian diet (Instituto Nacional de Estadística y Censos, 2011), and it is suitable for production in all the technologies. Lettuce yield in hydroponic greenhouses is three to four times larger than in soil crops due to steadier climate conditions resulting in higher growth rates, and to the multilevel cultivation of the mNFT technique which increases the crop densities (Ministerio de Agricultura y Ganadería, 2018). Since there is no available local data on iRTGs yield, it was set to the maximum yield in hydroponic greenhouses in the country considering that heat and CO_2 integration will increase the crop yields as suggested in the literature (Nadal et al., 2017).

Table 2. Yields and resource consumption for 1m² of lettuce production in the selected URF technologies

	Unit	eGR	RTG	iRTG	Source
Crop yield	kg	3.60	9.75	11.71	(Instituto Nacional Autónomo de Investigación Agropecuaria., 2008)(Mafla, 2015)
Water consumption	lt/day	4.04	1.03	1.03	(Mafla, 2015)(Francisco Medina, 2017)
Crop density	plants	12	24	24	(Instituto Nacional Autónomo de Investigación Agropecuaria., 2008)(Carrasco and Izquierdo, 1996)
Crop cycle	Days	80-90	31-52	31-52	(Instituto Nacional Autónomo de Investigación Agropecuaria., 2008)(Carrasco and Izquierdo, 1996)
Number of crops	crop/year	4	9	9	(Instituto Nacional Autónomo de Investigación Agropecuaria., 2008)(Carrasco and Izquierdo, 1996)

Edible-green roof (eGR), rooftop greenhouse (RTG), integrated rooftop greenhouse (iRTG)

4. Results:

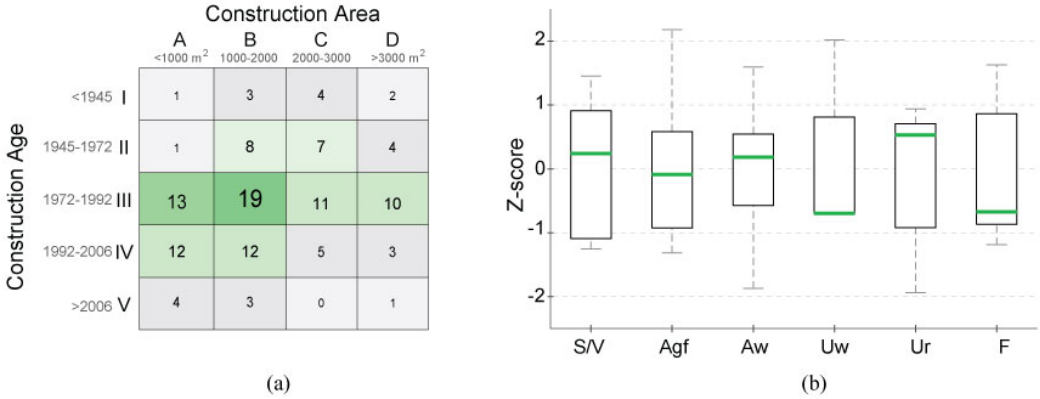
These results are the first application for the proposed evaluation model to a city case. The feasibility and sustainability of three rooftop-farming technologies to address the most significant deficiencies of existing schools in Quito –namely roof degradation, lack of green areas, and space inadequacy for implementing environmental projects- were quantified and compared. This section presents the results following the stages in the evaluation tool: city, building information, and farming technology.

4.1 City stage: schools' reference buildings

There are no previous studies on architectural typologies in the country; and as such, the first step was to create the typological classification. The initial school dataset -provided by the Ecuadorian Ministry of Education (2018)- includes all education centres in the metropolitan area of Quito. This dataset was downzised to public schools –in line with the TiNi initiative- in urban areas and crosschecked with the cities cadastre dataset. The final database includes 123 entries and depicts information on each school's ID, number of students, construction year, gross floor area, degradation state of the infrastructure, historical listings and construction system. The technical characteristics of each school were collected in individual datasheets using the Geographic Information System (GIS) of the Secretary of Territory, Habitat and Dwelling (2019), available technical drawings, photographs and site visits. The thermal properties for materials were taken from the Energy Efficiency Code for Residential Buildings (Ministerio de Desarrollo Urbano y Vivienda, 2018); and, the thermal transmittance (U-value) for building elements was calculated according to ISO 6946 and ISO 13370. The datasheet model is in Appendix C.

The typological classification yielded a 4x5 matrix of which only eight categories were significant (see Figure 3.a) as the remaining had less than five schools assigned to them and thus were below the specified threshold (4%). This is due to the scarcity of schools built prior to 1945 and after 2006. Each significant category is represented by one reference building unless the clustering shows that two or more subgroups are equally distributed. This classification allowed the selection of the most representative category in the schools' stock for conducting the pilot evaluation on rooftop-farming.

As specified in *Section 2.1,* the six data variables used for clustering were: compactness, ground floor area, external wall area, U-value of external walls, U-value of the roof, and the number of storeys. The descriptive data of the building sample is in Appendix D. Figure 3.b shows a boxplot of the standardised values for each variable. There is little variability in the sample regarding the thermal properties due to widespread use of single-leaf envelopes; this is reflected in the U-value boxplots, in which the median is closer to the quartile range limits. There were no multivariate outliers in the sample as all cumulative probabilities were above 0.09 for the chi-square distribution with six degrees of freedom –corresponding to the number of independent variables used.



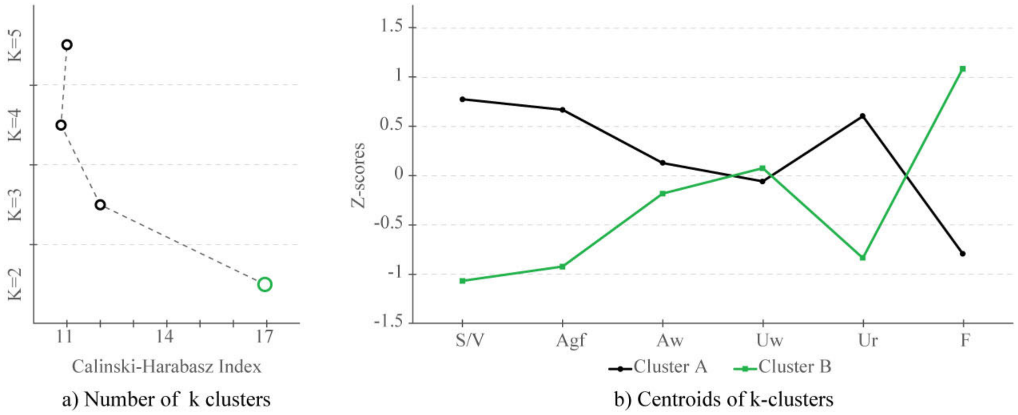
Construction Age	A <1000 m^2	B 1000-2000	C 2000-3000	D >3000 m^2
<1945 I	1	3	4	2
1945-1972 II	1	8	7	4
1972-1992 III	13	19	11	10
1992-2006 IV	12	12	5	3
>2006 V	4	3	0	1

(a)

(b)

Figure 3 (a) Typological classification of school buildings in Quito and (b) Descriptive data of the sample. Compactness (*S/V*), *ground floor area* (*Agf*), *external wall area* (*Aw*), U-value for walls (*Uw*), U-value for roofs (*Ur*), number of storeys (*F*).

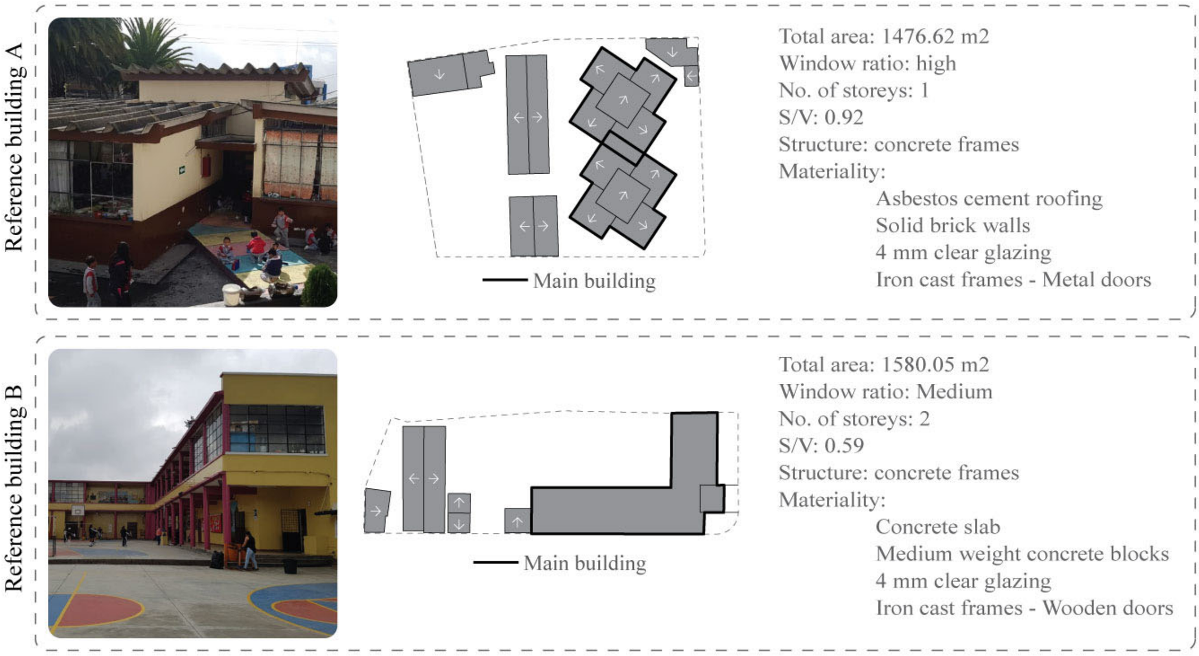
Two clusters obtained the highest Calinski-Harabasz index with a value of 16.97 (see Figure 4.a). Using k=2 in the K-mean algorithm resulted in 57% of the schools assigned to Cluster A and 43% to Cluster B. The ANOVA test showed significant variances ($\rho \leq 0.05$) for compactness, ground floor area, roof's U-value, and the number of storeys. The two remaining parameters did not present significant differences and, as such, were the least influential in the cluster formation. Figure 4.b shows the cluster's centroid values. The resulting school types are A) Disperse, one-storey buildings with pitch asbestos-cement roofs; and, B) Compact, two-storey buildings with flat concrete slabs. As both types are significant to the sample, two reference buildings were assigned and selected as the ones closest to their cluster centroids. Figure 5 provides an overview of the reference buildings. These results are in line with a 1995 study on construction systems in Quito's schools (Escuela Politécnica Nacional, 1995) which indentified two types of schools –modules and compact- based on field surveys.



a) Number of k clusters

b) Centroids of k-clusters

Figure 4. Selection of "k" number of clusters using Calinski Index and cluster centroids characterization using Z-scores



Total area: 1476.62 m2
Window ratio: high
No. of storeys: 1
S/V: 0.92
Structure: concrete frames
Materiality:
Asbestos cement roofing
Solid brick walls
4 mm clear glazing
Iron cast frames - Metal doors

Total area: 1580.05 m2
Window ratio: Medium
No. of storeys: 2
S/V: 0.59
Structure: concrete frames
Materiality:
Concrete slab
Medium weight concrete blocks
4 mm clear glazing
Iron cast frames - Wooden doors

Figure 5. School reference buildings, site plans of the entire school premises, and main descriptive characteristics

4.2 Building information stage: feasibility to implement rooftop farms in the reference buildings

The two reference schools were analysed based on the criteria defined in Section 2.2 to determine their feasibility to host rooftop farms and the necessary reconstruction interventions. As researchers expected that URF systems would be installed on the main buildings, the parameters described here correspond to these. A revision of the local construction codes revealed that rooftop greenhouses have to be considered close communal spaces; and as such, must use a maximum rooftop area of 30%, have a 5 meter setback from the main façades, and must comply with the maximum building height set in the city's urban planning policy. Table 3 shows the feasibility evaluation and details for the reconstruction interventions in each building according to the rooftop-farm technology applied.

Table 3. Required interventions in reference buildings to implement rooftop-farms according to feasibility criteria

Criteria	**Parameter**	**Reference school A**			**Reference school B**			**Source**
		eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**	
Feasibility criteria								
Economic	Roof maximum available area (m^2)	231	231	231	517	517	517	Cadastre
	Roof farm size (m^2)	231	50	50	517	100	100	Calc.
Environment	Solar radiation ($kWh/m^2/year$)	1326	1326	1326	1388	1388	1388	Calc.
Legal/urban	Area restriction	No	No	No	No	Yes	Yes	IRM
	Height restriction	No	Yes	Yes	No	Yes	Yes	IRM
Technical	Load capacity of the buildings (kg/m^2)	75	75	75	200	200	200	NEC 1977
	Roof slope (percentage)	10	10	10	0	0	0	GIS STHV
	Accessibility	No	No	No	No	No	No	Field visits
Reconstruction interventions								
	Roof replacement	Yes	Yes	Yes	No	No	No	
	Structural reinforcement	Yes	Yes	Yes	Yes	No	No	
	Access	Ext.	Ext.	Ext.	Int.	Int.	Int.	
	Fixings, pipes, ducts	No	No	Yes	No	No	Yes	
	Parapets	Yes	Yes	Yes	Yes	Yes	Yes	
	Legal permits	High	High	High	High	Low	Med	
	Construction risks	High	High	High	Med	Low	Low	

Edible-green roof (eGR), rooftop greenhouse (RTG), rooftop greenhouse (iRTG), Ecuadorian construction code (NEC), Secretary of Territory, Habitat and Dwelling (STHV), Metropolitan regulation report (IRM)

Reference school A has several one-storey buildings of which the predominant ones are two cross-shaped structures. These are independent buildings that were later interconnected by a lightweight metallic roof. The retrofitting is limited to one of these buildings as to decrease reconstruction impacts. The building's roof is composed of five independent shed-roofs; the centre roof is one meter above the others and thus will not be included in the intervention. Due to their slope and structural capacity, these roofs will be dismantled and replaced by flat concrete slabs, specifically 12 cm composite steel deck slabs with a minimum concrete compressive strength of 21 MPa and IPE metallic beams. The replacement of only one shed-roof is necessary for the installation of the rooftop greenhouse due to its area constraint (50-100 m^2). For the edible-green roof, the replacement of the four perimeter shed-roofs is considered. Additional interventions include the construction of an external staircase and parapets on the perimeter of the retrofitted roofs.

The main building in Reference School B is a 2-storey L-shaped building with a 20 cm unfinished concrete roof. The roof is currently inaccessible; thus, there is a need to construct a new flight of indoor staircases. Parapets will be built on the inner façades complementing the existent ones on the external façades. The roof slab load capacity is not compliant with current regulations for green roofs; as such, reinforcement of the beams is necessary only for the installation of the edible-green roof. The green roof will occupy the entire available area. As for compliance with urban policies, the RTG location is on the larger side of the building facing the indoor courtyard. Site plans for the reconstruction interventions for both schools and the solar radiation models are found in Appendix E.

4.3 Farming technology stage: sustainability of three rooftop farms

The requirements tree for the sustainability evaluation of rooftop-farming is composed of four requirements, ten criteria and seventeen indicators as shown in Table 4. The four requirements were: economic, environmental and social –in relation to the sustainability's pillars-, and technical –in relation to management practices. Since the rooftop-farm goal is to address the school's deficiencies, the tree included indicators closely related to the rooftop refurbishment, and excluded indicators on specific characteristics of the technologies like organic waste and product quality. Several indicators were also discarded for being outside the scope or for not being discriminatory and include governance aspects, neighbourhood acceptance, and food self-consumption. The stakeholders' preferences were also disregarded as not to induce a bias in the results.

Table 4. Requirements tree for the sustainability assessment of URF in schools in Quito.

Requirements (R_k)	**Criteria (C_k)**	**Indicator (I_k)**	**Unit**	**Shape**	**P_i**
R_1. Economic (25%)	C_1. Investment (50%)	I_1. Reconstruction/adaptation cost (40%)	$\$/m^2$	LD	1.00
		I_2. Installation cost (45%)	$\$$/m2	LD	1.00
		I_3. Disassembly cost (15%)	$\$/m^2$	LD	1.00
	C_2. Production costs (30%)	I_4. Maintenance cost (55%)	$\$/m^2$	LD	1.00
		I_5. Production cost (45%)	$\$/m^2$/crop	LD	1.00
	C_3. Benefits (20%)	I_6. Production yield (100%)	kg/m^2/year	CxI	3.00
R_2. Environmental (20%)	C_4. Energy efficiency improvement (20%)	I_7. Thermal insulation (50%)	W/m^{2}K	CvD	0.75
		I_8. Potential for thermal exchange (50%)	Points	CxI	3.00
	C_5. Site conditions (50%)	I_9. Rainwater harvesting capacity (100%)	Percentage	CxI	3.00
	C_6. Environmental impacts (30%)	I_{10}. GWP due to construction (40%)	$kgCO_2/m^2$	CxD	3.00
		I_{11}. GWP due to production (30%)	$kgCO_2/kg$	CxD	3.00
		I_{12}. Recycling potential (30%)	kg/m^2	CvI	0.75
R_3. Social (40%)	C_7. Education (35%)	I_{13}. Potential use as classroom (55%)	Points	CvI	0.75
		I_{14}. Affinity with curriculum (45%)	Points	CvI	0.75
	C_8. Legal (40%)	I_{15}. Complexity of legal compliance (100%)	Points	CxD	2.00
	C_9. Safety (25%)	I_{16}. Safety risk during construction (100%)	Points	CxD	2.00
R_4. Technical (15%)	C_{10}. Management (100%)	I_{17}. Qualified labour (100%)	Points	CvD	0.75

Global warming potential (GWP), linear decreasing (LD), convex increasing (CxI), convex decreasing (CxD), concave increasing (CvI), concave decreasing (CxD), shape factor (P_i)

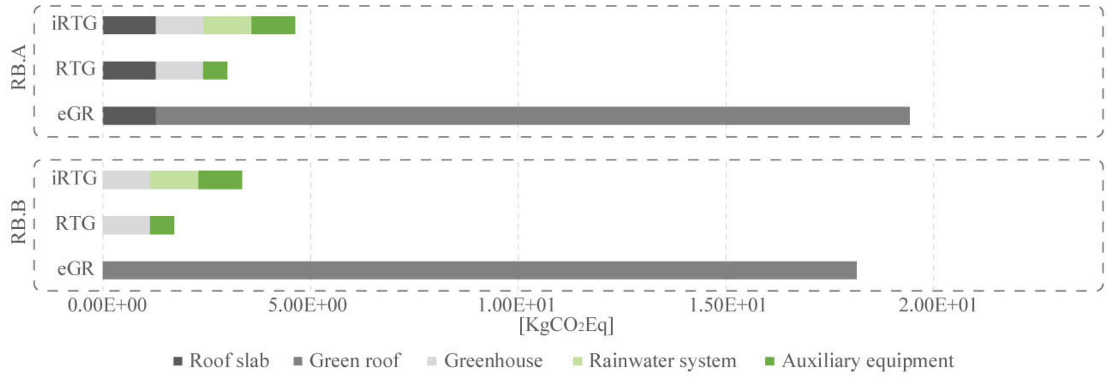
The social requirement was granted the highest importance due to the potential URF presents to act as learning spaces and experimental workshops on sustainability, and to the complexity of compliance with urban legislation as replicable less-demanding alternatives are preferred by the local administration. This prioritization of the social level is also found in other studies on UA -like those conducted in Berlin, Germany (Specht et al., 2016) and in Bologna, Italy (Sanyé-Mengual et al., 2018). Second in importance is the economic requirement favouring low-cost strategies due to limitations in public investment funds. Investment cost takes the larger share in the weighting as the maintenance and production costs are expected to fall within the bugdet assigned to the outgoing “TiNi” project. Since the high precipitation rate in the city causes floods and sewage overload, the capacity of the roof to harvest rainwater was considered the most important environmental criteria, giving the global warming potential and enegy efficiency similar lesser importance.

The sustainability evaluation was done for six scenarios resulting from the three URFs technologies application in the two reference schools. The indicators were quantified using different methods: economic indicators were calculated based on local construction prices, thermal insulation values were taken from scientific publications, and crop yields from national agriculture data. The potential for thermal exchange, social and technical indicators were valued using a 4-point scale (0=null, 1=low, 2=medium, 3=high) based on local literature. The global warming potential was taken from the simplified LCAs. The direct quantification of indicators are shown in Table 5; additional information on the calculation methods, life cycle inventories, and value functions used for each indicator are shown in Appendix F.

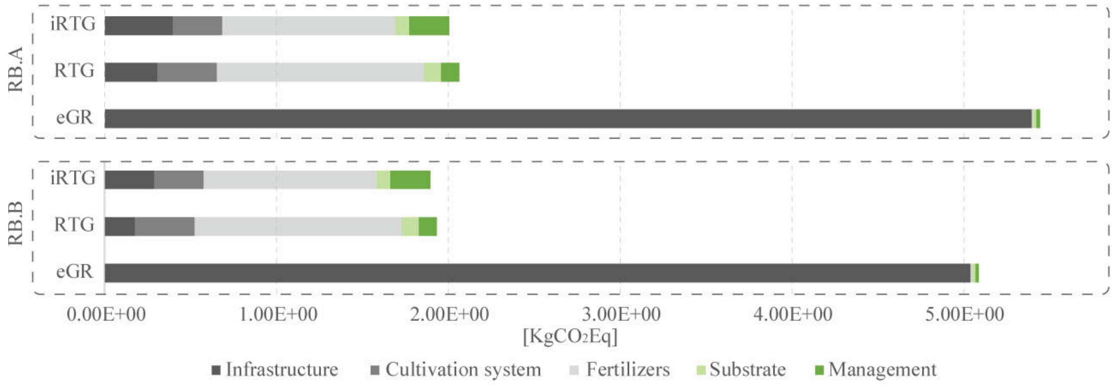
Table 5. Quantification of the indicators in the requirements tree for the three rooftop farms in each reference school

Indicator	**Unit**	**Reference school A**			**Reference school B**			**Ref.**
		eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**	
I1. Reconstruction cost	$\$/m^2$	254.47	316.30	331.44	59.96	28.60	38.69	(CAMICON, 2017)
I2. Installation cost	$/m2	47.33	71.70	130.96	47.33	64.65	101.73	(CAMICON, 2017; González, 2018)
I3. Disassembly cost	$\$/m^2$	13.40	15.00	17.26	13.40	15.00	17.26	(CAMICON, 2017)
I4. Maintenance cost	$\$/m^2$	9.76	13.36	21.09	9.76	13.36	21.09	(Pena, 2005; US Environmental Protection Agency, 2008)
I5. Production cost	$\$/m^2$/crop	0.22	0.30	0.30	0.22	0.30	0.30	(INIAP, 2008; Mafla, 2015)
I6. Production yield	kg/m^2/year	3.60	9.75	11.71	3.60	9.75	11.71	(INIAP, 2008; Mafla, 2015)
I7. Thermal insulation	W/m^2K	1.73	3.57	3.57	1.73	3.57	3.57	(Delor, 2011)
I8. Potential for thermal exchange	Points	4.00	2.00	9.00	4.00	2.00	9.00	(Specht et al., 2014)
I9. Rainwater harvesting capacity	Percentage	46.60	0.00	20.25	48.67	0.00	18.84	(STHV, 2017)
I10. GWP due to construction	$kgCO_2/m^2$	19.42	2.99	4.63	18.15	1.72	3.35	Calculated.
I11. GWP due to production	$kgCO_2/kg$	5.45	2.07	2.01	5.09	1.94	1.90	Calculated.
I12. Recycling potential	kg/m^2	0.81	0.88	1.04	0.81	0.88	1.04	Calculated.
I13. Potential use as classroom	Points	2.00	3.00	3.00	2.00	3.00	3.00	(Min Edu Ecu, 2017)
I14. Affinity with curriculum	Points	7.00	12.00	12.00	7.00	12.00	12.00	(Min Edu Ecu, 2017)
I15. Complexity of legal compliance	Points	3.00	5.00	5.00	3.00	6.00	6.00	(MDMQ, 2011)
I16. Safety risk during construction	Points	12.00	10.00	10.00	11.00	8.00	8.00	(Cajas and Vaca, 2018)
I17. Qualified labour	Points	8.00	10.00	11.00	8.00	10.00	11.00	(Carrasco and Izquierdo, 1996)

The indicator values varied significantly between reference schools regarding the roof's reconstruction cost, global warming potential and safety risks during construction; all of which are the result of the retrofit interventions defined in the previous section. Reference school A has the highest values in these indicators due to the dismantling process and the construction of the new roofs. The legal compliance indicator gives another clear difference between schools; in this, school B has stronger urban limitations due to its lack of construction setbacks and its construction height limitations. The remaining indicators are more discriminatory between farming technologies than between their hosts' reference building. Considering there is no local data on the life-cycle assessment for the farm technologies studied here, the simplified LCA results will be described in more detail.



a) Global warming potential of the construction of rooftop farms in reference schools



b) Global warming potential of the production of lettuce in rooftop farms in reference schools

Figure 6. Global warming potential for the construction and agriculture production of rooftop farms

The global warming potential (*GWP*) of the construction and agriculture production phases for the six scenarios are shown in Figure 6. Green roof construction has an impact of 18.15 kgCO$_2$eq/m^2; ten times the RTG and six times the iRTG values. The iRTG has almost twice the RTG impacts due to its rainwater harvesting system. However, the auxiliary equipment needed for the greenhouse-building integration does not significantly increase the GWP, signalling the potential to integrate exhaust airflows. These results are in line with available literature like 17.34 $kgCO_2eq/m^2$ for extensive green roofs (Lamnatou and Chemisana, 2015) or 21.1 $kgCO_2eq/m^2$ for a semi-intensive green roof (Peri et al., 2012). The lettuce production in the eGR has the highest GWP due to its infrastructure; however, its cultivation method (soil) is the lowest of the three farms with a value of 0.05 $kgCO_2eq$ per kg of lettuce. In contrast, the mNFT used in these greenhouses has an impact of up to 1.76 $kgCO_2eq$ per kg of lettuce. These results suggest that hydroponic systems can be a liability if not managed correctly.

The *global sustainability index* (GSi) and the contributions of the four requirements are shown in Figure 7. The edible-green roofs obtained the highest GSi with values of 0.62 and 0.65 for reference schools A and B, respectively. In general, implementing rooftop farms is more sustainable in school B as fewer reconstruction interventions are needed. The economic requirement is the most discriminant between reference schools, with differences of up to 0.18 due to reconstruction costs in school A. However, the educational benefits compensate the economic burden of replacing the rooftop; and as such, the reconstruction investment does not condition the implementation of URF.

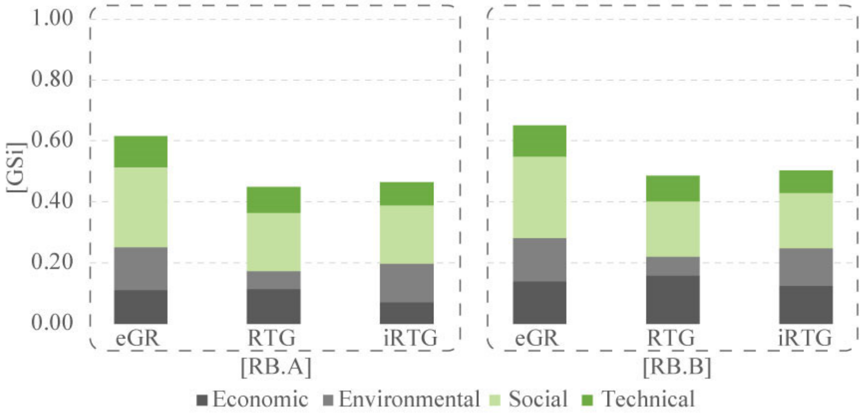


Figure 7. Sustainability index of URF with the requirements contribution on the final index results.

The economic dimension favours the rooftop greenhouse technology because its high production yields overcome the investment costs. In the case of the iRTGs, agricultural productivity does not compensate for the higher expenditure. The environmental, social and technical dimensions all promote the use of edible-green roofs; which is confirmed by the widespread use of green roofs on residential and commercial buildings in the city. The more influential parameters in the decision-making process were the system installation cost, the rainwater harvesting potential, and the lesser legal constraints for its implementation.

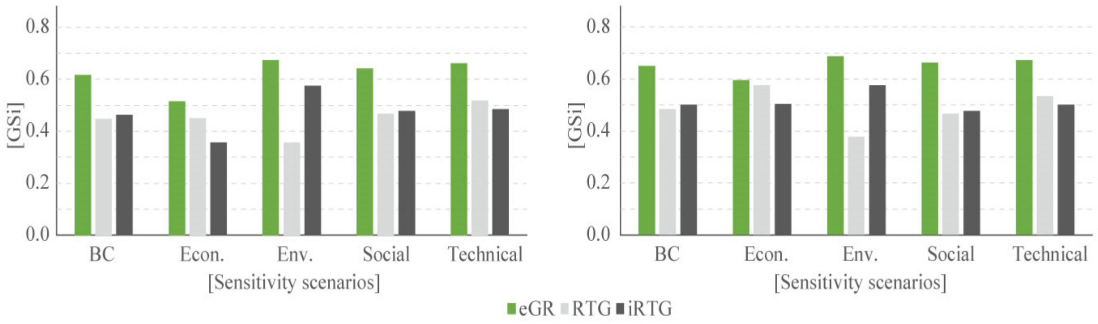
5. Discussion:

The evaluation model proposed is a new approach to the sustainability of rooftop-farming related to its host building; it considers the technical limitations posed by the building, the impacts of reconstruction, and the interaction with the building's users. Its main strengths are the use of reference buildings -to characterize the existing school stock- and of discriminating indicators –to quantify the sustainability. The preliminary step "typological classification" was meant to eliminate the significant influence of the variables "*construction age*" and "*construction area*" during the clustering process; identified as a necessary step in samples where construction practices varied significantly during the years e.g Serbian educational stock (University of Belgrade, 2018). However, the results for Quito reflected that construction practices remain unaltered since 1950, signalling the possibility of applying the clustering algorithm to the entire building stock (123 schools) without the typological subdivision. A review of the entire sample showed that seventy-eight school buildings share similar characteristics as those of Cluster A and thirty-five buildings as those in Cluster B, representing 63.4% and 28.4% respectively. The remaining ten schools date before 1950 and thus have different construction characteristics (compressed earth blocks masonry, wooden floors and pitch roofs with clay tiles).

The city school's rooftop area appropriate for farming purposes can be calculated by up-scaling the results of the feasibility assessment according to the number of schools in each cluster. This escalation renders an available area of 36,113 m^2 for green roofs and 7,400 m^2 for greenhouses, with a possible lettuce annual-yield of 130,000 kg and 72,150 kg respectively. Taking the average local consumption-per-capita of lettuce (0.56 kg/person/year), the edible-green roofs can supply lettuce to 232,143 persons and the greenhouses to 128,839 persons. The production yields for the three technologies exceed the consumption needs of the entire school population; and, the production surplus is enough to supply two-thirds of the remaining education centres (middle and high schools) in the case of green roofs and one-third in case of greenhouses.

Though the economic dimension is a crucial decision parameter in retrofitting, its influence in the final sustainability was lower than that of the social value of URFs. The predominance of the social dimension was the result of considering reconstruction as a way to foment ecological and sustainable living in the students. The sustainability quantification –based on experts weighing of the requirements tree- signal the edible-green roof technology as best suited to the study context due to its lower costs, rainwater harvest potential and compliance with planning codes. However, none of the evaluated technologies achieved a high global sustainability index due to contrasting values in the indicators. For example, edible-green roofs need lowest economic investments and so have the highest indexes for criteria C1 and C2; however, their low crop yield causes them to have the lowest index for C3 criteria. In this way, the results not only grade the URF alternatives and rank them in terms of their global sustainability, but provide valuable information on key improvement points.

The consistency of the global sustainability index in different weighing scenarios prove the relative objectivity of these results; although, the inclusion of techniques like Delphi and BIAS reduction could further improve their objectivity. The GSi index was recalculated in four scenarios: economic, environmental, social and technical. In each of these scenarios, a weight of 70% was given to its namesake requirement and 10% weights to those remaining, e.g. economic scenario (Economic 70%, Environmental 10%, Social 10%, Technical 10%). The results confirm the predominance of the edible-green roof over the RTG and iRTG models, and the stability of the GSi value under different scenarios with variations of less than 0.08 (see Figure 8). The iRTG technology underperformed as both its main advantages -reduction of the building energy intensity and extended agricultural seasons- are not viable in the study context. This is due to local climate conditions permitting year-round open-air farming and that these school buildings are not mechanically conditioned. The following paragraphs discuss the sustainability of each technology.



a) Reference school A

b) Reference school B

Figure 8. Global sustainability index of URF technologies in different weighting scenarios. BC (base case).

Edible green roof: this technology requires a low economic investment due to local production for all its components, large life span and minimum cultivation requirements. Its main setbacks are its low production yield and high added-structural weight. Its capacity to capture rainwater runoff and provide thermal insulation to the roof makes it the preferable choice due to local context conditions. Considering that appropriate substrates for eGR have a low percentage of organic matter, proper fertilisation is required to guarantee productivity and avoid nutrient runoff due to high precipitation. The productivity in eGR is low in comparison to the other systems and so future research should focus on optimising its yields.

Rooftop greenhouse: this rooftop-farm has a large profit margin due to high productivity and relatively low installation costs. Despite the mNFT technique being the most water-efficient, as its supply comes entirely from the grid and requires a high quantity of fertilisers, this technology is the most impacting in terms of global warming. Better sustainability results can be obtained by replacing the mNFT technique for other less contaminanting hydroponic systems. RTGs face urban and legal limitations -like usable area and building height- which complicate its dissemination. These constraints are related explicitly to this case study and extrapolation to other contexts is not recommended.

Integrated-rooftop greenhouse: rainwater harvesting and the use of building's exhaust air gives the iRTG a clear advantage over conventional greenhouses despite its increment in investment and maintenance costs. The integration building-iRTG reduces the water-grid supply needs to a third and increases its food yield by 20%. The most significant contribution of iRTGs is the reduction in energy needs for conditioning purposes (Delor, 2011); however, this benefit was neglected as schools in the city are non-conditioned. The sustainability for iRTGs is expected to increase in more severe climate conditions.

6. Conclusions and future work:

This article presented in detail the newly developed bottom-up model to evaluate rooftop farming alternatives in a city as a mean for sustainability. The strengths of this model include the use of reference buildings as accurate representatives of the building stock, and the quantification of a sustainability index based on customizable discriminating indicators. Using reference buildings avoided the difficulty in up-scaling the results from the cases studies to the city level; and, the combination of simplified LCAs, AHP, and seminars with experts gave objectivity to the sustainability assessment permitting an objective comparison and ultimately the selection of a farm technology tailored to each building. This model was used to assess the sustainability for the hypothetical implementation of three rooftop-farm technologies in the existing school stock in Quito, Ecuador.

Two reference schools accurately represented the city stock. In both schools, edible-green roofs obtained the highest sustainability index with values of 0.62 and 0.65, up to 37% above the other evaluated options. This is due to their larger rainwater harvesting capacity, thermal resistance and contribution to the increment of urban greenspaces. The city-wide application of edible-green roofs would result in a annual production yield of 130 Ton, almost twice the production of rooftop-greenhouses, and could suply the entire self-demand for the school population. The building-integrated agriculture alternatives had unexpected low indexes due to the city's particular climate conditions. However, and as all technologies had sustainability values below 0.70, significant improvements are needed in all the alternatives for this case study.

This is the first study on building typologies in the country, and sets a solid background for future research on rehabilitation, energy efficiency, and similar decision-making processes. City council and private stakeholders can use this model and its results to aid in the retrofitting or new construction of schools. However, adaptation to other contexts and retrofitting strategies would require revision of the configuration variables. In this sense, future studies will deal with the adaptation and application of this model to other geographic contexts and building typologies. Similarly, the effect of rooftop-farming -and other alternatives- on indoor thermal comfort and building's energy efficiency will be assessed in future projects.

Acknowledgements: The authors would like to thank all the experts who took part in the seminars for their time and support. A special thanks to PhD. Violeta Vargas for her support on the LCA quantification. Additional thanks to the Ecuadorian National Secretary of Higher Education, Science and Technology (SENESCYT) for awarding a research scholarship to Gabriela Ledesma (CZ02-000592-2018). The authors thank the Spanish Ministry of Economy and Competitiveness for awarding and funding the research projects Fertilecity-I (CTM2013-47067-C2-1-R) and Fertilecity-II (CTM2016-75772-C3-1-2-3-R); and, to the Catalan Government for the SGR funds (2014 SGR 1412). We acknowledge the financial support from the Spanish Ministry of Economy and Competitiveness, through the 'María de Maeztu' programme for Units of Excellence in R&D (MDM-2015-0552). The co-author Oriol Pons Valladares is a Serra Húnter Fellow. This article is part of a doctoral dissertation on the optimization of the buildings envelope through the combination of passive strategies tailored to individual surfaces.

Declarations of interest*:* none

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APPENDIX A:

Table A.1. Abbreviations used in the text in alphabetical order

Abbreviations	Relevant Values
AHP	Analytic Hierarchy Process
CED	Cumulative energy demand
CvD	Concave decreasing function
CvI	Concave increasing function
CxD	Convex decreasing function
CxI	Convex increasing function
eGR	Edible green roofs
GIS	Geographic information systems
GR	Green roofs
GSi	Global sustainability index
GWP	Global warming potential
IRM	Metropolitan Regulation Report of Quito
IRR	Internal return rate
iRTG	Integrated rooftop greenhouse
iVF	Indoor vertical farming
LCA	Life cycle assessment
LCC	Life cycle costs
LCI	Life cycle inventory
LD	Linear decreasing function
LDPE	Low density polyethylene
MIVES	Integrated Value Model for Sustainability Assessment
mNFT	Modified nutrient film technique
NEC	Ecuadorian construction code
NFT	Nutrient film technique
NPV	Net present value
OAF	Open air farming
PVC	Polyvinyl chloride
RB	Reference building
RTG	Rooftop greenhouse
RTG (c)	Climate controlled rooftop greenhouse
STHV	Secretary of Territory, Habitat and Dwelling of Quito
TiNi	Land of children for the good living
URF	Urban rooftop farming
VF	Vertical farming

APPENDIX B:

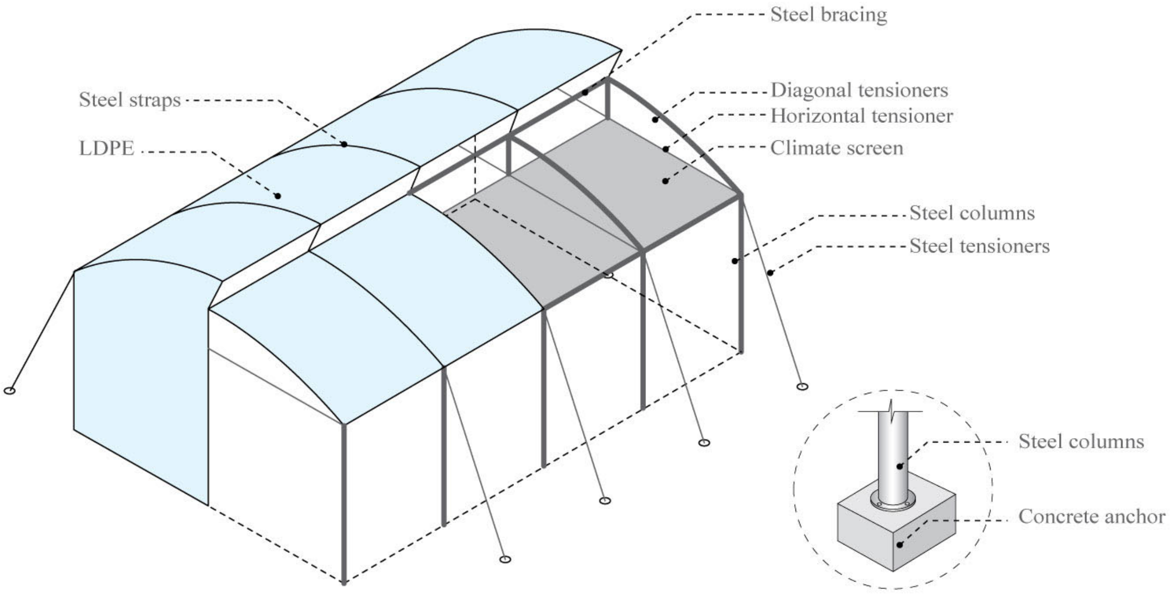


Figure B.1. Tropical vault greenhouse with description of structure and envelope elements. Adapted from (NOVACERO, n.d.)

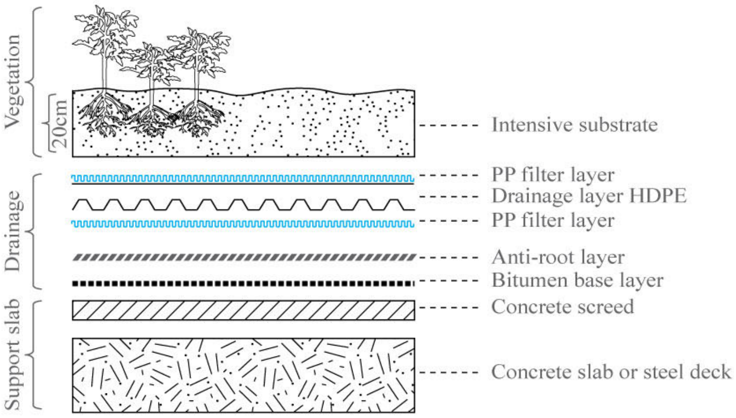


Figure B.2. Semi-intensive green-roof layers. Adapted from (Holguín, 2016)

APPENDIX C

Name: Q13
Address: Confidential
Parish: Historic district
Schedule: morning and afternoon
Construction year: 1990
Construction area: 1580.05
Classroom area:

ID **Q13**

Last renovation: Roof in pavillion B
No. of students: 631

Block ID	Storeys	No. of similar blocks	Block shape	Roof shape	WWR	Ground floor area	Perimeter	Height	Volume (V)	External walls area
A	2		L	Plana	AA	604.21	140.95	7.00	4229.47	986.65
B	1		Rec	2 aguas	A	226.39	67.14	3.50	792.37	234.99
C	1		Rec	2 aguas	M	44.56	27.84	2.40	106.94	66.82
OTHERS	1		Rec	Inclinada	M	84.70	53.79	2.40	203.28	129.10

Storeys (Avg):	1.70
Height (Avg):	5.90

Ground floor area (m2):	875.16
External wall area (m2):	1288.46

S/V (1/m):	0.59
V (m3):	5128.78

Pictures:

Schematic drawings:

Blocks ID

Constructive elements ID

Constructive elements properties:

Element	Description	U-value	Area	UxA
C1	Waterproofing (pure) Cement screed Reticular slab with ligth hollow concrete interjoists 20cm Cement render	3.23	604.21	1951.60
C2	Cement tiles on metallic framework and false ceiling of plasterboard with mineral fibers	3.51	270.95	951.03
F1	Cement render Hollow concrete block 15cm Plaster	2.35	1288.46	3027.87
S1	Gravel Concrete solid slab Mortar adhesive Ceramic tiles	3.06		
V1	Clear glazing 6mm with iron frames	5.7		
P1	Aluminium sheets Iron cast structure	5.88		
P2	Panel door with 11mm wood panels	3.24		

Cadastre drawings:

Average U-value walls:	2.35
Average U-value roofs:	3.32

Figure C.1. Datasheet model for sample school buildings.

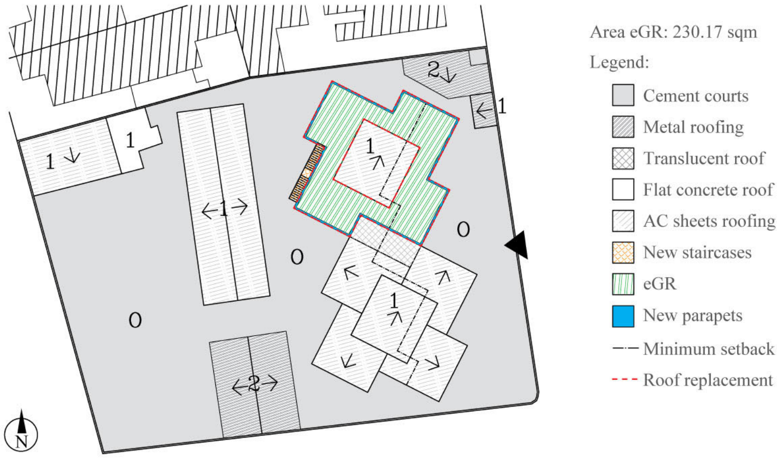
APPENDIX D:

Table D.1. Values of the independent variables used in the k-mean algorithm, cluster membership of each school, and distance to its clusters centroids.

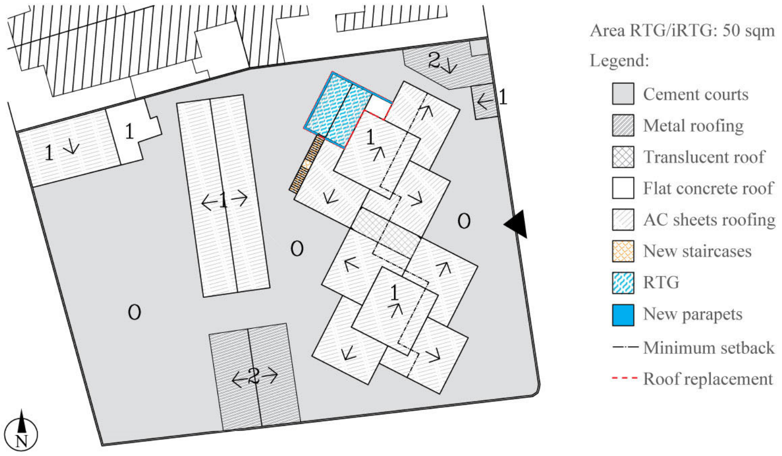
ID	Built Year	Total area (m^2)	No. Students	S/V	Agf (m^2)	Aw (m^2)	Uw (W/m^{2}k)	Ur (W/m^{2}k)	F (No.)	Outlier probability	Cluster ID	Distance to centroid
Q1	1980	1996.40	255	1.06	1883.29	1381.01	2.35	3.34	1.00	0.12	1	1.7897
Q2	1986	1522.98	844	0.65	680.95	1623.03	2.50	2.69	2.10	0.09	2	2.1291
Q3	1980	1330.43	708	0.62	683.30	1099.98	2.35	3.48	2.00	0.11	2	1.7991
Q4	1985	1014.84	411	0.64	579.23	797.70	2.35	2.81	1.80	0.38	2	1.9472
Q5	1988	1761.56	464	1.04	1540.85	1284.50	2.35	3.56	1.10	0.88	1	0.9672
Q6	1975	1651.68	637	0.60	801.16	1301.28	2.83	2.81	2.00	0.31	2	2.1422
Q7	1976	1476.62	638	0.92	1267.45	1307.07	2.53	3.32	1.20	0.78	1	0.8064
Q8	1991	1528.48	833	0.97	1240.91	1127.80	2.35	3.44	1.20	0.97	1	0.9360
Q9	1980	1992.00	615	0.85	1281.89	1535.08	2.35	3.52	1.40	0.82	1	1.6783
Q10	1977	1612.84	1016	1.03	1279.81	1349.63	2.35	3.56	1.20	0.96	1	0.8293
Q11	1990	1539.25	471	1.09	1459.01	1287.35	2.65	3.46	1.10	0.83	1	1.1731
Q12	1980	1229.84	602	0.74	565.25	1021.77	2.35	2.81	1.80	0.52	2	1.3872
Q13	1990	1580.05	631	0.59	875.16	1288.46	2.35	3.32	1.70	0.31	2	1.1070
Q14	1975	1614.40	1226	1.17	1458.18	1189.54	2.72	3.52	1.00	0.56	1	1.7290
Q15	1985	1557.54	697	1.07	1140.20	1483.64	2.35	3.48	1.20	0.5	1	1.2151
Q16	1990	1117.25	203	0.62	564.83	799.18	2.77	2.92	1.80	0.34	2	2.3417
Q17	1980	1246.55	1145	0.91	873.38	1195.78	2.75	3.22	1.20	0.36	1	2.3147
Q18	1980	1869.45	386	0.61	958.26	1591.86	2.39	3.48	1.90	0.36	2	2.4230
Q19	1990	1083.00	302	1.16	1028.70	953.72	2.35	3.49	1.10	0.4	1	1.7358

APPENDIX E:

Edible green roof in Reference Building A



Rooftop greenhouse in Reference Building A



Solar Radiation in Reference Building A

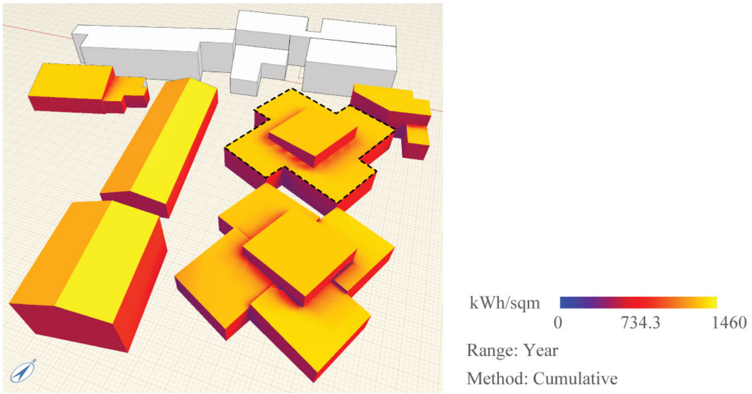
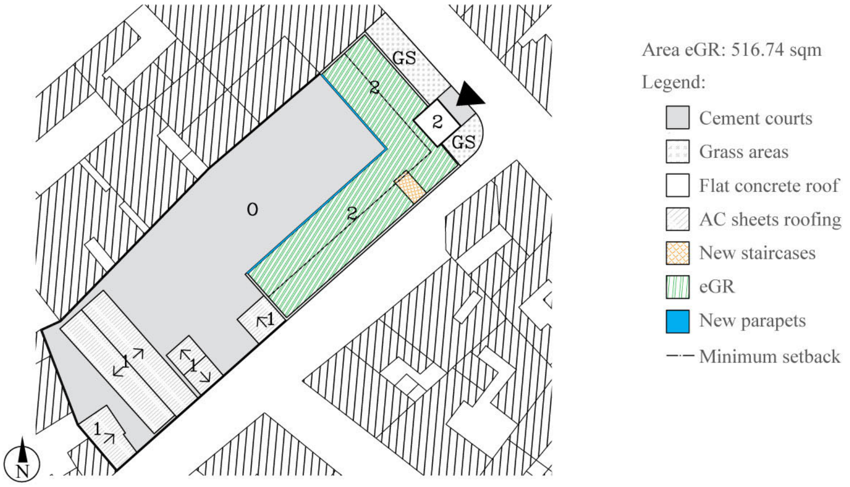


Figure E.1. Reference School A site plans of the URF systems detailing the reconstruction interventions, and results of the solar radiation simulation

Edible green roof in Reference Building B



Rooftop greenhouse in Reference Building B

Solar Radiation in Reference Building B

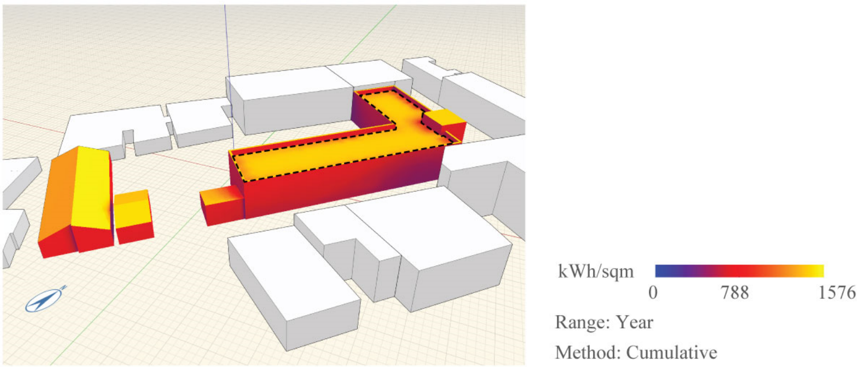


Figure E.2. Reference School B site plans of the URF systems detailing the reconstruction interventions, and results of the solar radiation simulation

APPENDIX F:

F.1 Definition of the value function for MIVES model

Table F.1. Parameters required for the definition of the value functions

	Unit	Shape	X_{max}	X_{min}	C_i	K_i	P_i	References
I1. Reconstruction/adaptation cost	$\$/m^2$	LD	340	0	340	0.0	1.00	(Camára de la Industria de la Construcción, 2017)
I2. Installation cost	$\$$/m2	LD	135	0	135	0.0	1.00	(Camára de la Industria de la Construcción, 2017; González, 2018)
I3. Disassembly cost	$\$/m^2$	LD	18	0	18	0.0	1.00	(Camára de la Industria de la Construcción, 2017)
I4. Maintenance cost	$\$/m^2$	LD	22	0	22	0.0	1.00	(Pena, 2005; US Environmental Protection Agency, 2008)
I5. Production cost	$\$/m^2$/crop	LD	1	0	0.5	0.0	1.00	(Instituto Nacional Autónomo de Investigación Agropecuaria, 2008; Mafla, 2015)
I6. Production yield	kg/m^2/year	CxI	12	0	3	0.2	3.00	(Instituto Nacional Autónomo de Investigación Agropecuaria, 2008; Mafla, 2015)
I7. Thermal insulation	W/m^{2}K	CvD	4	0	2	0.9	0.75	(Delor, 2011)
I8. Potential for thermal exchange	Points	CxI	9	0	2	0.1	3.00	(Specht et al., 2014)
I9. Rainwater harvesting capacity	Percentage	CxI	50	0	20	0.7	3.00	(Secretaría de Territorio Habitat y Vivienda, 2017)
I10. GWP due to construction	kgCO_2/m^2	CxD	20	0	6	0.1	3.00	Calculated
I11. GWP due to production	kgCO_2/kg	CxD	6	0	3	0.7	3.00	Calculated
I12. Recycling potential	kg/m^2	CvI	2	0	0.7	0.8	0.75	Calculated
I13. Potential use as classroom	Points	CvI	3	0	1	0.9	0.75	(Ministerio de Educación del Ecuador, 2017)
I14. Affinity with curriculum	Points	CvI	13	0	6	0.8	0.75	(Ministerio de Educación del Ecuador, 2017)
I15. Complexity of legal compliance	Points	CxD	6	0	2	0.8	2.00	(Municipio del Distrito Metropolitano de Quito, 2011)
I16. Safety risk during construction	Points	CxD	15	0	9	0.8	2.00	(Cajas and Vaca, 2018)
I17. Qualified labour	Points	CvD	15	0	9	0.7	0.75	(Red de Cooperación técnica en Producción de Cultivos Alimenticios, 1996)

LD (linear decreasing); CxI (convex increasing); CxD (convex decreasing); CvI (concave increasing); CxD (concave decreasing); MinEdu (Ecuadorian Ministry of Education); NTAU (Quito Architecture Code); MinAgro (Ecuadorian Ministry of Agriculture)

F.2 Data used in the life-cycle assessment

Table F.2. Energy balance of Ecuador as of December 2018. Data taken from (Agencia de Regulación y Control de Electricidad, 2019)

Electricity mix 2018	**%**
Hydroelectric	70.00
Eolic	0.26
PV	0.13
Biogas	0.16
Biomass	1.37
Thermal MCI	17.03
Thermal Turbogas	4.66
Steam	6.00
Import	0.39

Table F.3. Power data of construction equipment. Data taken from the machinery specification sheets.

Type	**Type of fuel**	**Characteristics**	**Power (kW)**	**Fuel (gl/hr)**
Concrete pump	Diesel	Putzmeister BSA 1005 D3B C		4.90
Concrete vibrator	Diesel	INGCO GVR-2		0.30
Welder	Electricity	INDURA 302 AC/DC	9.00	
Mini crane elevator	Diesel	BAGANT PE-30		0.50
Hydraulic crane	Electricity	PALFINGER PK 10000	0.55	
General construction activities	Electricity	General	1.81	

Table F.4. Origin, distance and transport type for construction materials used in the LCA

Material	**Origin**	**Distance (km)**	**Transport type**
Materials:			
Steel (joists, beams, pipes)	Quito, Ecuador	30	Lorry <32 Ton EURO 3
Steel (deck slab)	Daule, Ecuador	382	Lorry >32 Ton EURO 3
Steel (galvanized sheets)	Latacunga, Ecuador	95	Lorry <32 Ton EURO 3
Steel (wires)	Aloag, Ecuador	50	Lorry <32 Ton EURO 3
Concrete reinforced	Quito, Ecuador	30	Lorry <32 Ton EURO 3
Cement cast plaster floor	Quito, Ecuador	30	Lorry <32 Ton EURO 3
Waterproof layers (bitumen membranes)	Pintag, Ecuador	50	Lorry 7.5 Ton EURO 3
LDPE (greenhouse cat.)	Soacha, Colombia	1100	Lorry >32 Ton EURO 3
GFRP	Cuenca, Ecuador	481	Lorry >32 Ton EURO 3
HDPE	Pintag, Ecuador	50	Lorry 7.5 Ton EURO 3
PVC (pipes, pots, tank)	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Polyethylene PE (tubes)	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Polypropylene PP (drippers)	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Climate screen	Santander, Colombia	1400	Lorry >32 Ton EURO 3
Equipment:			
Water pump 40W	Texas, USA	4378	Freight ship
	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Centrifugal fan	Shanghai, China	16458	Freight ship
	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Flow meter	Miami, USA	2889	Aircraft, freight
Digital timer	Miami, USA	2889	Aircraft, freight
Agricultural production:			
Fertilizers NPK	Novorossiysk, Russia	13810	Freight ship
	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Rice husk	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Coir	Guayaquil, Ecuador	431	Lorry >32 Ton EURO 3
Compost	Quito, Ecuador	30	Lorry 7.5 Ton EURO 3
Substrate	Quito, Ecuador	30	Lorry 7.5 Ton EURO 3
End of life			
Recycling facility	Quito, Ecuador	30	Lorry 7.5 Ton EURO 3
Landfill	Quito, Ecuador	30	Lorry 7.5 Ton EURO 3

Data for product origins taken from (Observatory of Economic Complexity, n.d.)

Transport type taken from (Oviedo Carrillo, 2015)

Table F.5. Life cycle inventories of the three URF technologies. Functional unit m^2/year. Lifespan 50 years

Input	Material / Process	Life Span	Unit	eGR	RTG	iRTG	Ref
Roof construction							
Joists	Steel low alloyed (90% recycled) [production, hot tempering]	50	kg	4.71E-01	4.71E-01	4.71E-01	Cal.
Slab	Steel low alloyed (90% recycled) [production, cold tempering]	50	kg	2.24E-01	2.24E-01	2.24E-01	Cal.
	Concrete for building construction with cement CEM II/A [production]	50	kg	4.99E+00	4.99E+00	4.99E+00	Cal.
	Cement mortar [production]	50	kg	1.20E+00	1.20E+00	1.20E+00	Cal.
Transport	Lorry >32 Ton EURO 3	-	tkm	1.30E-01	1.30E-01	1.30E-01	Cal.
Transport	Lorry 16-32 Ton EURO 3	-	tkm	1.86E-01	1.86E-01	1.86E-01	Cal.
Machinery	Electricity	-	kWh	5.98E-02	5.98E-02	5.98E-02	Cal.
	Diesel [burned in building machine]	-	kWh	2.40E-03	2.40E-03	2.40E-03	Cal.
Intensive green roof							
Growing medium	Expanded clay [production]	-	kg	2.32E+01	-	-	(Vacek et al., 2017)
	*Slag [rock crushing]	-	kg	1.48E+01	-	-	(Vacek et al., 2017)
	*Brick shards [rock crushing]	-	kg	7.60E+00	-	-	(Vacek et al., 2017)
	Peat moss [production for horticultural use]	-	kg	4.40E+00	-	-	(Vacek et al., 2017)
	Compost [biowaste at collection point]	-	kg	4.40E+00	-	-	(Vacek et al., 2017)
Separation and filtration	Polypropylene granulate [production, extrusion, plastic film]	50	kg	1.72E-01	-	-	(Vacek et al., 2017)
Drainage layer	High density polyethylene granulate [production, extrusion, plastic film]	50	kg	6.40E-01	-	-	(Vacek et al., 2017)
Waterproofing	Bitumen adhesive compound [hot production]	50	kg	9.60E-01	-	-	(Vacek et al., 2017)
Root barrier	Bitumen adhesive compound [hot production]	50	kg	1.90E+00	-	-	(Vacek et al., 2017)
	Polyester resin [production]	50	kg	1.00E-01			(Vacek et al., 2017)
Transport	Lorry 3.5-7.5 Ton EURO 3	-	tkm	3.57E+00	-	-	Cal.
Machinery	Diesel [burned in building machine]	-	kWh	3.40E-02	-	-	Cal.
Waste	**Landfill	-	kg	5.82E+01	-	-	Cal.
Greenhouse							
Structure	Steel low alloyed (90% recycled) [production, hot tempering]	50	kg	-	8.36E-01	8.36E-01	(Sanyé-Mengual et al., 2015)
Anchor	Concrete for building construction with cement CEM II/A [production]	50	kg	-	2.12E-01	2.12E-01	(Sanyé-Mengual et al., 2015)
Enclosure	Low density polyethylene granulate [production, extrusion, plastic film]	4	kg	-	1.50E-01	1.50E-01	(Sanyé-Mengual et al., 2015)
Climate screen	Polyester resin [production]	5	kg	-	8.00E-03	8.00E-03	(Sanyé-Mengual et al., 2015)
	Aluminium cast alloy [production, wire drawing]	5	kg	-	8.00E-03	8.00E-03	(Sanyé-Mengual et al., 2015)
Transport	Lorry >32 Ton EURO 3	-	tkm	-	1.87E-01	1.87E-01	Cal.
Transport	Lorry 16-32 Ton EURO 3	-	tkm	-	3.14E-02	3.14E-02	Cal.
Transport	Lorry 3.5-7.5 Ton EURO 3	-	tkm		3.64E-02	3.64E-02	Cal.
Machinery	Diesel [burned in building machine]	-	kWh	-	9.50E-03	9.50E-03	Cal.
Recycling	**Recycling process	-	kg	-	8.36E-01	8.36E-01	Cal.
Waste	**Landfill	-	kg	-	3.78E-01	3.78E-01	Cal.
Rainwater harvesting system							
Water tank	GFRP polyamide [production, injection moulded]	50	kg	-	-	9.73E-02	(Sanjuan-Delmás et al., 2018)
Pipes	High density polyethylene granulate [production, extrusion, plastic pipes]	10	kg	-	-	7.25E-03	(Sanjuan-Delmás et al., 2018)

Pump	Cast iron [production, metal working for iron product manufacturing processing]	10	kg	-	-	1.71E-03	(Sanjuan-Delmás et al., 2018)
	Steel low alloyed (90% recycled) [production, metal working for steel product manufacturing processing]	10	kg	-	-	9.38E-02	(Sanjuan-Delmás et al., 2018)
Transport	Freight ship	-	tkm	-	-	4.18E-01	Cal.
Transport	Lorry >32 Ton EURO 3	-	tkm	-	-	8.79E-02	Cal.
Transport	Lorry 3.5-7.5 Ton EURO 3	-	tkm	-	-	6.36E-03	Cal.
Machinery	Diesel [burned in building machine]	-	kWh	-	-	1.80E-03	Cal.
Waste	**Landfill	-	kg	-	-	2.00E-01	Cal.
Auxiliary equipment							
Centrifugal fan	Steel low alloyed (90% recycled) [production, metal working for steel product manufacturing processing]	10	kg	-	-	5.80E-02	Cal.
Ventilation ducts	Steel low alloyed (90% recycled) [production, cold tempering]	10	kg	-	-	1.38E-01	Cal.
Flow meter	Cast iron [production, metal working for iron product manufacturing processing]	10	kg	-	-	2.82E-02	(Sanjuan-Delmás et al., 2018)
	High density polyethylene granulate [production, injection moulding]	10	kg	-	-	1.48E-03	(Sanjuan-Delmás et al., 2018)
Digital timer	High density polyethylene granulate [production, injection moulding]	10	kg	-	3.04E-03	3.04E-03	(Sanjuan-Delmás et al., 2018)
	Electronics [production for control units]	10	kg	-	1.60E-04	1.60E-04	(Sanjuan-Delmás et al., 2018)
Support for channels	High density polyethylene granulate [production, injection moulding]	5	kg	-	4.74E-02	4.74E-02	(Sanjuan-Delmás et al., 2018)
	Steel low alloyed (90% recycled) [production, wire drawing]	5	kg	-	4.62E-02	4.62E-02	(Sanjuan-Delmás et al., 2018)
	Polypropylene [production, injection moulding]	5	kg	-	4.51E-02	4.51E-02	(Sanjuan-Delmás et al., 2018)
Adhesive	Adhesive [tetrahydrofuran production]	10	kg	-	8.22E-07	8.22E-07	(Sanjuan-Delmás et al., 2018)
Solvent	Solvent [organic, methy acetate, production]	10	kg	-	2.21E-06	2.21E-06	(Sanjuan-Delmás et al., 2018)
Pump and pressure switch	Cast iron [production, metal working for iron product manufacturing processing]	10	kg	-	5.20E-02	5.20E-02	(Sanjuan-Delmás et al., 2018)
	Steel low alloyed (90% recycled) [production, metal working for steel product manufacturing processing]	10	kg	-	6.10E-03	6.10E-03	(Sanjuan-Delmás et al., 2018)
	High density polyethylene granulate [production, injection moulding]	10	kg	-	3.06E-03	3.06E-03	(Sanjuan-Delmás et al., 2018)
Transport	Freight ship	-	tkm	-	2.68E-01	1.22E+00	Cal.
Transport	Aircraft, freight	-	tkm	-	9.24E-03	9.48E-02	Cal.
Transport	Lorry >32 Ton EURO 3	-	tkm	-	4.58E-02	7.08E-02	Cal.
Transport	Lorry 16-32 Ton EURO 3	-	tkm	-	4.68E-03	1.06E-02	Cal.
Machinery	Diesel [burned in building machine]	-	kWh	-	-	3.60E-03	Cal.
Waste	**Landfill	-	kg	-	2.03E-01	4.29E-01	Cal.
Transport	Lorry 3.5-7.5 Ton EURO 3	-	tkm	-	6.09E-03	1.29E-02	Cal.

* Material from production waste. Impacts considered only for processing stages

** Waster recycling practices are excluded from the system boundaries

Table F.6. Life cycle inventories for 1 kg of lettuce in the three URF technologies.

Material / Process	**Life Span**	**Unit**	**eGR**	**RTG**	**iRTG**	**Ref.**
Cultivation system						
Polyvinylchloride [production, extrusion, plastic pipes]	10	kg	-	1.22E-01	1.01E-01	(Sanyé-Mengual et al., 2015)
Polyvinylchloride [production, injection moulding]	10	kg	-	1.88E-03	1.57E-03	(Sanyé-Mengual et al., 2015)
Polyvinylchloride [production, injection moulding]	10	kg	-	1.68E-02	1.40E-02	(Sanyé-Mengual et al., 2015)
Low density polyethylene granulate [production, extrusion, plastic pipes]	10	kg	6.11E-04	4.25E-03	3.54E-03	(Sanyé-Mengual et al., 2015)
Polypropylene granulate [production, extrusion, plastic pipes]	10	kg	5.65E-04	2.10E-04	1.75E-04	(Sanyé-Mengual et al., 2015)
Polyvinylchloride [production, extrusion, plastic pipes]	10	kg	1.83E-04	1.73E-04	1.44E-04	(Sanyé-Mengual et al., 2015)
Polypropylene granulate [production, injection moulding]	10	kg	1.83E-04	6.83E-04	5.70E-04	(Sanyé-Mengual et al., 2015)
Lorry >32 Ton EURO 3	-	tkm	6.65E-04	6.28E-02	5.23E-02	Cal.
Crop inputs						
Electricity	-	kWh	-	2.82E-01	3.13E-01	(Sanyé-Mengual et al., 2015)
Water consumption (tap water)	-	ltr	6.39E+01	4.64E+0	2.71E+00	(Francisco Medina, 2017; Mafla, 2015)
Water consumption (rainwater)	-	ltr	3.15E+01	-	1.16E+00	(Francisco Medina, 2017; Mafla, 2015)
Compost [bio-waste at collection point]	-	kg	5.83E-02	-	-	(Sanyé-Mengual et al., 2015)
NPK compound (15-15-15) [production]	-	kg	8.33E-03	3.38E-01	3.19E-01	(Mafla, 2015; Sanyé-Mengual et al., 2015)
Calcium nitrate [production]	-	kg	-	1.29E-01	1.07E-01	(Mafla, 2015; Sanyé-Mengual et al., 2015)
Potassium nitrate [production]	-	kg	-	1.86E-01	1.55E-01	(Mafla, 2015; Sanyé-Mengual et al., 2015)
Expanded clay [production]	-	kg	3.22E-02	-	-	(Sanyé-Mengual et al., 2015)
*Slag [rock crushing]	-	kg	2.06E-02	-	-	(Sanyé-Mengual et al., 2015)
*Brick shards [rock crushing]	-	kg	1.06E-02	-	-	(Sanyé-Mengual et al., 2015)
Peat moss [production for horticultural use]	-	kg	6.11E-03	-	-	(Sanyé-Mengual et al., 2015)
Rice husk [production]	-	kg	-	4.15E-02	3.46E-02	Cal.
Coconut, husked [production]	-	kg	-	4.15E-02	3.46E-02	Cal.
Freight ship	-	tkm	1.15E-01	8.67E-05	7.21E-02	Cal.
Lorry >32 Ton EURO 3	-	tkm	7.42E-03	3.58E-02	3.21E-02	Cal.
Waste management						
**Recycling process		kg	-	8.57E-02	7.14E-02	Cal.
**Landfill	-	kg	1.63E+01	2.99E-01	2.85E-01	Cal.
Lorry 7.5 Ton EURO 3	-	tkm	4.88E-01	1.15E-02	1.07E-02	Cal.

F.3 Calculation of economic indicators:

The calculation of all construction costs was based on published prices by the Construction Agency for the year 2017 (Camára de la Industria de la Construcción, 2017). Costs taken from non-local sources were scaled according to Equation 1.

$$\text{Cost}_{\text{final}} = \text{Cost}_{\text{ref}} \times \text{Purchasing Power Parity} \times \text{Inflation rate} \quad \textit{Eq.F.1}$$

Reference costs before 2017 were brought to net present value according to Equation 2.

$$\text{Cost}_{\text{Final}} = \text{Cost}_{\text{Ref}} \times \text{Inflation rate} \; \textit{Eq.F.2}$$

Table F.7. Quantification of indicator I_1. Roof adaptation costs scaled to the respective URF area

Material	**Reference School A**			**Reference School B**		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Roof disassembly	2.09	2.42	2.42	-	-	-
Clearance of materials	3.34	3.86	3.86	-	-	-
Steel joists	110.09	127.21	127.21	-	-	-
Composite steel deck slab	40.23	46.48	46.48	-	-	-
Indoor ceiling	22.16	25.60	25.60	-	-	-
Disassembly and renovation of electrical fixtures	10.99	12.69	12.69	-	-	-
Disassembly of plumbing fixtures	0.98	1.31	1.31	0.20	-	-
Screed	10.66	12.32	12.32	10.98	-	-
Plumbing fixtures	1.52	1.04	1.04	1.42	0.31	0.31
Parapet	10.34	20.13	20.13	2.58	13.57	13.57
Stairwell	3.25	14.99	14.99	4.50	10.36	10.36
Structural reinforcement to existing slab	-	-	-	31.13	-	-
Mechanical fixtures	-	-	12.83	-	-	8.55
Total direct costs	215.65	268.05	280.88	50.81	24.24	32.79
Indirect costs (18%)	38.82	48.25	50.56	9.15	4.36	5.90
Total costs	**254.47**	**316.30**	**331.44**	**59.96**	**28.60**	**38.69**

Table F.8. Quantification of indicator I_2. Installation costs of the rooftop farms scaled to their respective areas.

Material	**Reference School A**			**Reference School B**		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Green roof (including all layers except substrate)	33.04	-	-	33.04	-	-
Substrate e=25cm	2.48	-	-	2.48	-	-
Irrigation system	4.59	-	-	4.59	-	-
Greenhouse structure (steel, bolt structure and plastic)	-	24.00	24.00	-	24.00	24.00
NFT fixings	-	15.13	15.13	-	15.13	15.13
Rainwater fixtures and tank	-	-	17.09	-	-	9.28
Lighting fixtures	-	11.12	11.12	-	9.10	9.10
Shading net	-	2.60	2.60	-	2.60	2.60
Extraction fan	-	-	19.75	-	-	9.87
Ducts and fixings	-	-	12.24	-	-	11.70
Electric board	-	7.91	9.06	-	3.95	4.53
Total direct costs	40.11	60.76	110.99	40.11	54.78	86.21
Indirect costs (18%)	7.22	10.94	19.98	7.22	9.86	15.52
Total costs	**47.33**	**71.70**	**130.96**	**47.33**	**64.65**	**101.73**

Table F.9. Quantification of indicator I_3. Disassembly cost of the farms not including the dismantling of the roof.

Material	**Reference School A**			**Reference School B**		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Greenhouse light structure	-	6.09	6.09	-	6.09	6.09
NFT structure	-	1.02	1.02	-	1.02	1.02
Mechanical fixings	-	-	1.38	-	-	1.38
Electrical fixings	-	1.02	1.56	-	1.02	1.56
Plumbing fixings	1.02	1.02	1.02	1.02	1.02	1.02
Soil clearance	2.33	-	-	2.33	-	-
Waterproofing	2.36	-	-	2.36	-	-
Clearance	3.12	1.03	1.03	3.12	1.03	1.03
Cleaning	2.53	2.53	2.53	2.53	2.53	2.53
Total direct costs	11.36	12.71	14.63	11.36	12.71	14.63
Indirect costs (18%)	2.04	2.29	2.63	2.04	2.29	2.63
Total costs	**13.40**	**15.00**	**17.26**	**13.40**	**15.00**	**17.26**

Table F.10. Quantification of indicator I_4. Maintenance cost for each rooftop farm technology.

	Reference School A			**Reference School B**			
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**	**Ref**
Reference cost	16.14	20.45	32.28	16.14	20.45	32.28	(Pena, 2005; US Environmental Protection Agency, 2008)
Purchasing power parity	0.54	0.54	0.54	0.54	0.54	0.54	(The World Bank, 2017)
Inflation rate	1.12	1.21	1.21	1.12	1.21	1.21	(Instituto Nacional de Estadística y Censos, 2018)
Final cost	**9.76**	**13.36**	**21.09**	**9.76**	**13.36**	**21.09**	

Table F.11. Quantification of indicator I_5. Production cost of lettuce per square meter

	Reference School A			**Reference School B**			
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**	**Ref**
Production cost per m^2	0.17	0.29	0.29	0.17	0.29	0.29	(Instituto Nacional Autónomo de Investigación Agropecuaria, 2008; Mafla, 2015)
Inflation rate	1.31	1.01	1.01	1.31	1.01	1.01	(Instituto Nacional de Estadística y Censos, 2018)
Final cost	**0.22**	**0.30**	**0.30**	**0.22**	**0.30**	**0.30**	

F.4 Calculation of environmental indicators:

For the rainwater harvesting capacity the urban planning codes set a precipitation scenario of 50mm (Secretaría de Territorio Habitat y Vivienda, 2017) and an absorption rate for green roofs of 50% (Municipio del Distrito Metropolitano de Quito, 2011). The following equations were used.

The total precipitation in the rooftop is:

$$V_{total} = Area_{roof} \times 50mm \quad \textit{Eq.F.3}$$

The green roofs rainwater harvest is:

$$V_{eGR} = Area_{eGR} \times 50mm \times absorption\ rate \quad \textit{Eq.F.4}$$

The integrated rooftop-greenhouse rainwater harvest is:

$$V_{iRTG} = Area_{RTG} \times 50mm \quad Eq.F.5$$

Table F.12. Quantification of indicator I_8. Potential for thermal exchange with the host building

	Reference School A			Reference School B		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Rainwater use	2	0	3	2	0	3
Exhaust air	0	0	3	0	0	3
Evaporative cooling	0	2	3	0	2	3
Greywater reuse	2	0	0	2	0	0
Total	**4**	**2**	**9**	**4**	**2**	**9**

**Scores: 0 (null); 1 (low); 2(Medium); 3 (High)*

Table F.13. Quantification of indicator I_9. Rainwater harvesting capacity of each rooftop farm technology scaled to the URF area

	Reference School A			Reference School B		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Area of the roof (m^2)	246.96	246.96	246.96	530.87	530.87	530.87
Total precipitation (m^3)	12.34	12.34	12.34	26.54	26.54	26.54
Area rooftop farm (m^2)	230.17	0	50	516.74	0	100
Rainwater harvested (m^3)	5.75	0	2.5	12.91	0	5.0
Harvesting capacity (%)	**46.60**	**0.00**	**20.25**	**48.67**	**0.00**	**18.84**

F.5 Calculation of social and technical indicators:

Table F.14. Quantification of indicator I_{14}. Affinity of the rooftop farm to the school curriculum considering the experimental activities guidelines of the Ministry of Education (Ministerio de Educación del Ecuador, 2017)

EXPERIMENTAL ACTIVITIES	Reference School A			Reference School B		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Characteristics of the physical states of matter		1	1		1	1
Germination process	1	1	1	1	1	1
Healthy meals	1	1	1	1	1	1
Water quality		1	1		1	1
Worms in agriculture	1			1		
Simple machines		1	1		1	1
Simple substance mixes		1	1		1	1
Types of soils (substrates)	1	1	1	1	1	1
Hydroponic crops		1	1		1	1
Global warming		1	1		1	1
Leafs structure	1	1	1	1	1	1
Vegetable grow	1	1	1	1	1	1
Photosynthesis	1	1	1	1	1	1
Total points	**7**	**12**	**12**	**7**	**12**	**12**

Table F.15. Quantification of indicator I_{15}*. Complexity of legal compliance for implementation of rooftop farms*

LEGAL REQUIREMENTS	Reference School A			Reference School B		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Technical review process	1	1	1	1	1	1
Local planning regulations	0	1	1	0	1	1
Construction permit	1	1	1	1	1	1
Height restriction	0	0	0	0	1	1
Area restriction	0	1	1	0	1	1
Fire safety restrictions	1	1	1	1	1	1
Total points	**3**	**5**	**5**	**3**	**6**	**6**

Table F.16. Quantification of indicator I_{16}*. Safety risks during the construction of the rooftop farms according to the Ecuadorian Regulation for Health and Safety in Construction* (Ministerio de Trabajo y Empleo, 2008)

RISKS	Reference School A			Reference School B		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Fall protection	3	3	3	3	3	3
Urban protection	1	1	1	3	3	3
Lifting machinery	3	3	3	2	1	1
Hazardous substances and materials	2	0	0	2	0	0
Intrusion on usable spaces	3	3	3	1	1	1
Total points	**12**	**10**	**10**	**11**	**8**	**8**

**Scores: 0 (null); 1 (low); 2(Medium); 3 (High)*

Table F.17. Quantification of indicator I_{17}*. Qualified labor needed for the production and maintenance of the rooftop farms*

ACTIVITY	Reference School A			Reference School B		
	eGR	**RTG**	**iRTG**	**eGR**	**RTG**	**iRTG**
Crop nutritional requirements	2	3	3	2	3	3
Pruning and harvesting	2	1	1	2	1	1
Monitoring of equipment	0	2	3	0	2	3
Moisture and irrigation	1	3	3	1	3	3
Pest control	3	1	1	3	1	1
Total points	**8**	**10**	**11**	**8**	**10**	**11**

**Scores: 0 (null); 1 (low); 2(Medium); 3 (High)*

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