Rooftop greenhouses in educational centers: A sustainability assessment of urban agriculture in compact cities

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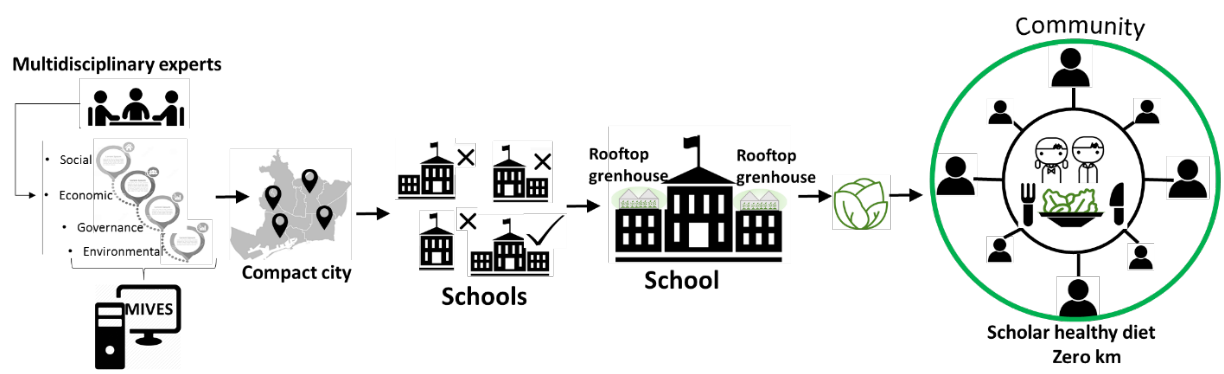
GRAPHICAL ABSTRACT



Highlights

- A new method is proposed for scholar-social rooftop greenhouse (RTG) selection
- Economic, environment, social & governance regards were used as indicators
- MIVES model provides objective sustainability options for scholar RTG application
- Social & governance were the most discriminatory indicators for schools selection
- RTGs provide environmental, social, educational & nutritional advantages in schools

ABSTRACT

Today, urban agriculture is one of the sustainability strategies most used to improve cities metabolism. Schools have an important role for the implementation of sustainability master plans, due the social, educational, family and social cohesion character that promote and are a key element for the development of urban agriculture. In this sense, the main objective of this research is to develop a procedure to evaluate the potential for implementation of rooftop greenhouses (RTGs) in schools of compact cities. The fact to generate a dynamic assessment tool capable of identifying and prioritizing schools with the highest potential for a RTG implementation also represents a great ally for the environmental, social, and nutritional education of younger generations.

The methodology has four-stages (Pre-selection criteria, Selection necessities, Sustainability analysis and Sensitivity analysis and selection of the best alternative) and economic, environmental, social and governance aspects are considered. It makes use of the Multi Attribute Utility Theory and Multi-Criteria Decision Making, through the Integrated Value Model for Sustainability Assessments model and the participation of two panels of multidisciplinary specialists, for the generation of a unified index of sustainability, guarantying the objectivity of the selection.

This methodology has been applied and validated in a study case corresponding to 11 schools in Barcelona (Spain). Due to the social nature of the proposed methodology, the case with the highest school staff and parents' association support (social and governance indicators) obtained the highest sustainability index (S11), with a considerable difference (45%) over the worst case (S3) that did not have the school staff and parents support. Finally, the method showed to be appropriate, adaptable, and trustworthy to get an objective decision about urban and vertical agriculture implementation in schools, supporting the Sustainable development goals and the circular economy.

Keywords

Integrated Value Model for Sustainability Assessment, Schools, Multi-Criteria Decision Making, Circular economy, Vertical farming, Rooftop greenhouse

Abbreviations

Multi Attribute Utility Theory (MAUT)

Multi-Criteria Decision Making (MCDM)

Integrated Value Model for Sustainability Assessment (MIVES)

Rooftop greenhouse (RTG)

1. INTRODUCTION

Cities have an environmental footprint that exceeds their natural biocapacity and rely heavily on imported resources of rural areas (Baabou et al., 2017; Doughty and Hammond, 2004; Ewing et al., 2010; Galli et al., 2017). Metropolis consumption of resources and energy is constantly increasing to maintain the lifestyle of the residents of these urban areas, which represent a serious threat to the environment (Girardet, 2014). To transform modern cities in more sustainable environments it is necessary to develop a more circular economy where fewer resources are consumed and more are reused or recycled. In 1992, Agenda 21 proposed, within the United Nations, the compact city with mixed land uses as an urban model for achieving sustainability (United Nations, 1992).

Within the context of sustainability strategies of cities, adapting vacant and unused rooftops to productive spaces is a documented strategy among city planners (Carter and Keeler, 2008; Elzeyadi et al., 2009). Rooftops have a great potential for exploitation as they occupy 21% to 26% of all built-up areas (Getter and Rowe, 2006) that can be used for the introduction of urban agriculture (UA), the use of photovoltaic cells and rainwater harvesting, as multifunctional strategies for rooftops to increase sustainability, save energy and reduce environmental impacts (Soler and Rivera, 2010).

In this sense, UA alternatives can be classified in two main groups that include numerous additional options. A) Traditional form (mainly, land and conventional irrigation): private gardens, community gardens, backyard farming. B) Technological form (soil-free growing system, light-emitting diode - LED – lighting and others): green walls, rooftop greenhouses, green roofs, (Nadal et al., 2015). Both forms generate significant benefits in the three pillars of sustainable development (Cohen and Reynolds, 2014). Specifically, rooftop greenhouses (RTGs), described as greenhouses built on rooftops of buildings using soil-less culture systems to produce vegetables (Cerón-Palma et al., 2012a; Nadal et al., 2017b, 2015; Sanyé-Mengual et al., 2015) stand out within the technological forms of UA. And in compact cities with high residential density, mixed land use and limited access to spaces, rooftop greenhouses (RTGs) can provide the opportunity to produce food with maximum efficiency, minimizing production impacts and optimizing usually unused space (Nadal et al., 2017b). Also, the cultivation of plants and vegetables in urban RTGs increase the supply of nutritious vegetables and promotes food security and sovereignty in highly populated areas (Nadal et al., 2017b).

In this compact city model, the service sector operates in diverse types of buildings which meet a wide variety of uses (Pérez-Lombard et al., 2008). Its area covers commonly all public buildings and usually have various action lines, among them: administration, education, culture, sports, housing, health and others (Oliver-Solà et al., 2013). Usually school centers have big buildings to provide a good service; are located in different areas of the city; have a good infrastructure of services; are constructed of durable materials and with bearing profiles (in many cases they are considered as residual spaces).

Also schools have a environmental education approach, which can permeate beyond the students, reaching the families and neighbors of the area. Also, RTG's are a viable alternative for the strengthening of this approach, because they have several qualitative and quantitative characteristics that can lead to a good synergy in social, environmental and economic aspects compared to other possibilities. So transforming school rooftops to "agro-green spaces" (spaces with potential for urban agriculture development) can be a viable and very useful strategy to improve the metabolism performance and the circular economy of compact cities. In this context, this research analyzes quantitatively the possibility of implementing RTGs in schools as a strategy for the environmental, social and economic improvement of the development of a compact city.

1.1. Opportunities of urban agriculture in educational centers

At present, educational facilities have an important role in the development of students, families and neighbors in the sensitivity with respect to environmental sustainability and social cohesion, through educational activities related to food and UA (Sanjuan-Delmás et al., 2016). Referring to this, the Scholar Agenda 21 was created to involve educational centers in the environmental improvement of the city, increase their level of sustainability, include environmental education in the centers and involve children, parents and teachers in different environmental issues (United Nations, 1992). Specifically, Green Schools Program is a priority action included in Agenda 21 for the reorientation of education towards sustainable development applied around the world, through work plans related to the environment and integrated into their curricula (Somwaru, 2016; United Nations, 1992).

In addition to the social values that schools can develop, educational buildings in compact cities of the Catalonian Mediterranean area present compatible structural-architectural characteristics for the development of the UA in the form of rooftop greenhouse: a) schools have prime locations within compact neighborhoods; b) educational buildings have often oversized roof structures such as reinforced concrete slabs that allow the development of various activities, being capable to withstand the minimum loads for the implementation of a RTG, among other possible applications (Al-Otaibi et al., 2015); c) schools often have large percentages of areas with roofs (usually, relatively large unoccupied rooftops) (Al-Otaibi et al., 2015), which makes them a type of building with high potential for the implementation of an RTG; and d) school centers usually have kitchens and dining rooms where products obtained by the RTG may be prepared and consumed, though they can also be sold outside. In this form, schools have the possibility to close a cycle of UA.

All this means that schools have a high potential for sustainable and agro-green development in cities by RTGs. Compared to other alternatives such as photovoltaic panels and rainwater harvesting, RTG's have more social benefits such as the promotion of social cohesion, sovereignty and food security. Specifically, this implementation has numerous benefits. Direct ones, with the support to the creation of jobs and local economy; promotion of environmental and nutrition education and sensitization; and improvement of health and quality of life, upgrading abandoned tops and strengthening city security; among others (Cerón-Palma et al., 2012b; Sanyé-Mengual et al., 2013). Indirect ones, through the efficient use of resources, such as reducing food packaging and transportation distances of fresh food. It is important to note that urban schools in Europe use a high percentage of their own roofs spaces as playgrounds due to their high constructed density, which can be a limitation to this new application (Pons Valladares, 2009).

UA is an issue increasingly investigated, with special emphasis on the benefits it brings to urban population. However, studies that focus on implementation of UA in the form of RTGs are limited, and even more so when it comes to the UA in educational service buildings. In this context, this article presents a study of the integration of RTGs in

Barcelona educational centers constructed during a specific period in order to focalize the wide typology of school buildings currently existing.

1.2. Objectives

The main objective of the research conducted is to develop a procedure to evaluate the potential for implementation of rooftop greenhouses (RTGs) in schools within a compact city in the Mediterranean area.

There are two specific objectives of this study:

- To generate a dynamic assessment model and tool based on the Multi Attribute Utility Theory, Multi-Criteria Decision Making and Value Analysis theories capable of prioritizing schools for the location of the most sustainables RTGs.
- To assess the school buildings of a selected and more or less homogeneous sample in Barcelona in order to test the developed model, improve it and determine the most sustainable school building/s as location for RTGs, considering different scenarios.

2. METHODOLOGY

This study is the first version of a new methodology for RTG prioritazion and implementation in school centers. The method uses and unifies different tools and guides for a better identification of the best school rooftop alternative. The method addresses the urban planning implementation of RTGs in service (school) buildings in urban areas, though it can be applied to more general contexts. The study posits RTGs composed of soil-less culture system, hydroponics, in order to reduce potential problems of structural overload of the building and make responsible use of water.

The methodology of this research consists of four stages (Fig. 1). First stage, pre-selection criteria (1): it exposes initial or basic feasibility conditions for implementing RTGs on a building considering agricultural, economic, legal and urban planning, as well as technical factors. Pre-selection criteria purpose is to extract an initial sample, discarding the cases where the construction of an RTG is not possible or acceptable. Second stage, selection necessities (2): divided into two parts, architectural function and social participation. Its function is to reduce the initial sample to the most favourable cases in accordance with both building configuration and stakeholders (teachers, students, their families, neighbors, …) interests in order to be able to study them in more detail.

Third stage, sustainability analysis (3): assessment using the Integrated Value Model for Sustainability Assessment (MIVES). MIVES is a Multi Criteria Decision Making (MCDM) methodology based on the Multi Attribute Utility Theory (MAUT) and value function concept in order to carry out quantitative and objective assessments. This methodology has been used before to develop similar sustainability assessment tools that have been applied successfully in quite different fields (Viñolas, 2010; Viñolas et al., 2009a). And finally, the last stage (4): Sensitivity analysis and selection of the best alternative. Based on the sustainability analysis, it is possible the selection of the best alternative with the highest sustainability index for RTG implementation.

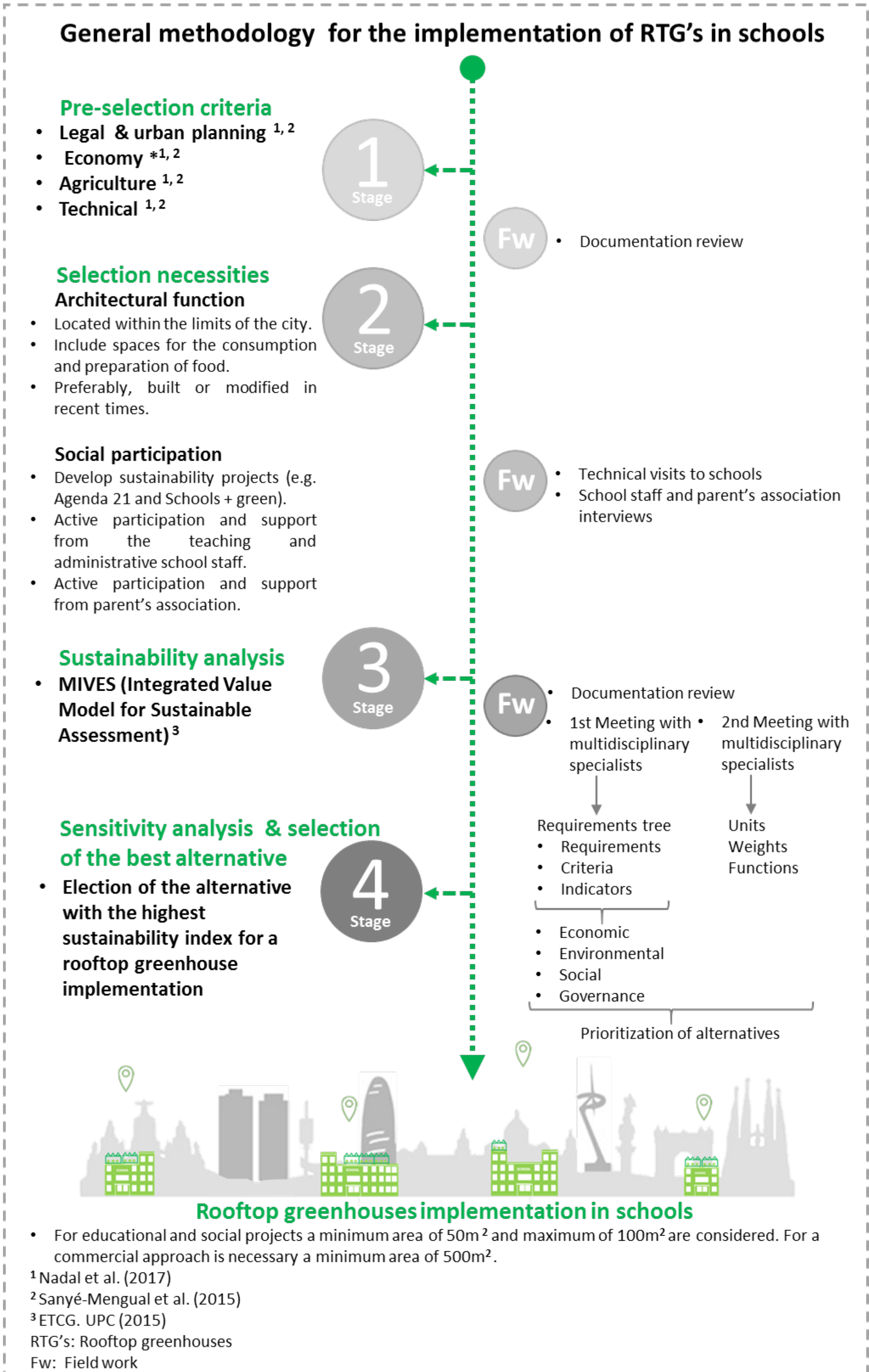


Fig. 1. General methodology stages proposed for the implementation of RTG in schools.

2.1. Application of the proposed methodology

2.1.1. Pre-selection criteria

This part includes the basic conditions for checking the construction feasibility of the rooftop system. This paper uses standards defined by Nadal et al., (2017a) and Sanyé-Mengual et al. (2015), and relios on a bibliographic review. Both guides help to determine the potential implementation of RTGs in non-residential areas. The basic criteria for the identification of a rooftop with potential to RTG implementation, are:

- Legal and urban planning criterion: it is mandatory to accomplish urban codes, as well as building and safety technical codes.
- Economic criterion: For educational and social approach a minimum area of $50m^2$ and maximum of $100m^2$ is considered, because the objective is only self-consumption. $50m^2$ RTG has been considered to be the minimum acceptable dimension to develop an educational and nutritional school project in conditions of reduced space. And $100m^2$ is the maximum considered, because in a larger area the process of crop maintenance can be laborious. For the present research we used this approach.

  For a commercial approach a minimum area of $500m^2$ is necessary, because is possible to recover the initial investment of the construction through the sale of the surplus product.
- Agricultural criterion: a roof free of elements that divide the surface is needed; in addition to this, the roof must have a minimum amount of sun radiation of 1900-2000MJ/m^2 year or 13-14MJ/m^2day to make crop growing possible.
- Technical criterion: the roof must have a slope no greater than 10% (flat roof) and a minimum load capacity of 200kg/m^2 (primarily concrete).

2.1.2. Selection necessities

Architectural function prioritizes the following three functional requirements (it is necessary that the building meets all them):

- Priority location within the city limits. A school located within the city limits offers several advantages: it influences a wide range of action within the neighborhood in terms of sustainability education, strengthens social cohesion, lacks space for growth and is usually a milestone within the neighborhood.

- Architectonic spaces for the consumption and preparation of food. If a school has the spaces necessary for the preparation and consumption of food, it promotes proximity consumption. That in turn directly influences the food of the students and potentiates the environmental education imparted in the institution when closing the circle of food consumption.
- Preferably, built or modified in recent times. A new building or a modified recently building (no more than 15 years) facilitates the work of adaptation (which may be necessary) for the RTG construction and of work spaces related to the crop because the building have structural and architectural facilities for a correct RTG implementation. Older buildings can also be considered if they meet the corresponding technical and structural conditions.

About the Social participation, and in order to ensure the success of the initiative, emphasis is initially placed on the following points to be fulfilled simultaneously:

- It is necesary the development of some project or initiative in favor of sustainability (e.g. Agenda 21, Green school, ISO 14000 or others).
- Active participation and suport from the teaching and administrative school staff is desirable.
- Active participation and suport from parents' association is desirable.

It is nowadays imperative, before planning the implementation of an RTG in a school, checking for programs or projects of educational or social characteristics that promote cohesion within the community, because these programs help to define actions and benefits that urban agriculture can offer and thus achieve success. In this sense, due the importance of the programs of implementation of RTGs, the parents association and the school's staff are great allies in order to develop, in the context of specific projects, the benefits of the implementation of RTGs in compact cities.

The information for the second step (Selection necessities) is collected through school visits and interviews with the school staff and parent's association. The structure of the interview is variable, but must be based on the points exposed in Architectural function and Social participation. The Annex Table A.1. shows an example of some questions that can be asked.

2.1.3. Sustainability analysis

MIVES quantitatively assesses each of the alternatives that can solve a generic problem. To do so it gives a single total value index as well as partial value indexes. It is a general tool to support decision making but it has mostly been used to measure the degree of sustainability of the problem evaluated (Aguado et al., 2006; Roca-Martín et al., 2009; Rojí, 2006; Viñolas et al., 2009a).

MIVES's strengths, relevant in this case, are that combines: (i) a specific holistic discriminatory tree of requirements; (ii) the assignation of weights for each tree member; (iii) the value function concept, leading to individual and global non-dimensional indexes from indicators quantification and weighing; and (iv) seminars with specialists (if needed) to define the aforementioned parts (Alarcon et al., 2010; Pons et al., 2016). The requirements tree is a crucial part of MIVES, being a hierarchical structure in which the characteristics of the processes or products to be appraised are defined in a structured mode at several – usually three - levels: requirements (the most general ones), criteria (in both, a breakdown is established for structuring the problem), and indicators (the most specific ones, that require individual quantification)

Fig. 2 shows MIVES' phases to reach a sustainability index (or another type of index in the case of different decision making processes). However, for this study, only rather the MIVES process main phases are developed to facilitate the understanding. The MIVES phases of this study are:

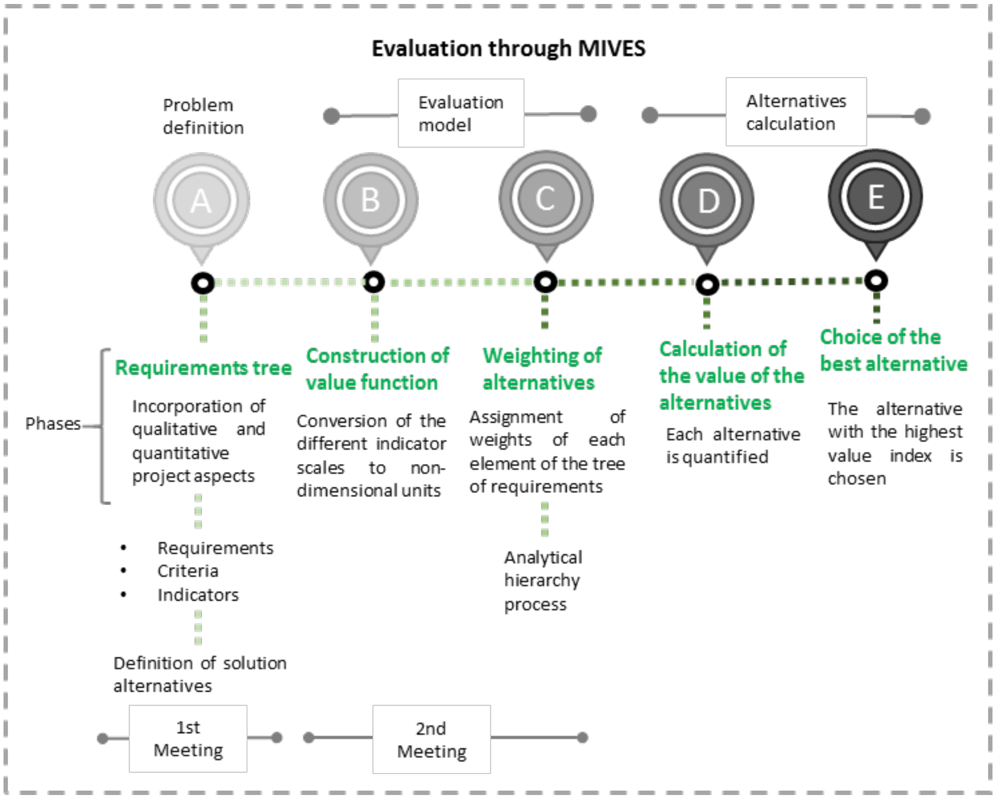


Fig. 2. MIVES' phases to reach the sustainability index.

A. Requirements tree: the limits of the system are defined and the boundary conditions established. The aspects that will be taken into account in the decision (requirements, criteria and indicators) are sorted in a branched way. This phase is development by a 1^{st} meeting with multidisciplinary experts, minimum 10 people. The configuration of this panel must respond to the needs and purpose of the study.
B. Construction of value functions: mathematical relationships to obtain quantities from 0 to 1 (or other range) of all aspects of the last branch of the decision tree (indicators) are determined. This phase is development by a 2^{nd} meeting with multidisciplinary experts. It is advisable to extend the previous panel of multidisciplinary specialists, at least 20 people, to have more diverse points of view and specialization.
C. Weight of alternatives: the relative importance of each of the aspects is established in relation to the others belonging to the same branch of the decision tree through Analytical Hierarchy Process (Russo and Camanho,

2015). This phase is development by a 2nd meeting with multidisciplinary experts.

D. Calculation of the value of the alternatives: the final quantitative index is obtained for each of the alternatives proposed through aggregation of individual values.
E. Prioritization of alternatives in accordance with the indexes obtained.

2.1.4. Sensitivity analysis and selection of the best alternative

After carrying out the sustainability analysis, the options or alternatives with the highest sustainability indexes (or just the highest one) are obtained. The best alternatives usually have a balance between the requirements (in this case economic, environmental, social and governance aspects) considered in the requirements tree.

A sensitivity analysis is performed to verify the choice of the alternative with the highest sustainability index. This analysis focuses on adding extreme scenarios in which each of the requirements are given a percentage weight much greater than those granted to the rest of the requirements. For example, if you have three requirements (R1, R2, R3), in one of the extreme scenarios (A scenario) the requirement R1 is given a weight of 80%, R2: 10% and R3: 10%; and in other scenario (B scenario), for R1: 10%, R2:80% and R3: 10%. After analyzing the extreme scenarios, it is possible to verify that the chosen alternative (with the highest sustainability index) in step 3 of the present methodology (section 2.1.3) is the best for the implementation of a rooftop greenhouse.

2.2. Study case

Barcelona, capital city of the Catalonia region, is located in the northeast of Spain (41º 12'–41º 48' N and 1º 27'–2º 46' E) with Mediterranean maritime climate. It is conformed by the municipality of Barcelona and numerous adjacent large and small towns, positioning itself as one of the most dense and urbanized regions of Europe (15,873 inhabitants/km^2) (Ajuntament de Barcelona, 2017). The municipality of Barcelona is considered a large, diverse and compact urban region (Catalán et al., 2008).

Since the 1950s, it has experienced an accelerated process of land consumption. Between 1960 and1980 migrations from rural areas increased and Barcelona population grew from 1.56 to 1.75 million inhabitants (Tombolini et al., 2015). The actual urban shape, limited by the sea, mountains and other municipalities, is formed by the progressive saturation of the internal core that limits the future growth of the city (Serra et al., 2014). Soil occupation, loss in agricultural land and decrease in settlement density are important indications of landscape changes and robust indicators of the new directions taken by urbanization (Tombolini et al., 2015).

In Catalonia more than 400 school buildings were built during the 2000s due to important population movements and facilities improvement (Pons and Aguado, 2012; Pons and Wadel, 2011). In this sense, Barcelona educational network (excluding university centers) consists of 934 schools of all levels of education distributed throughout the city (within the 10 educational districts) (Ajuntament de Barcelona et al., 2014; Consorci d'Educació de Barcelona, 2015). 400 of these centers are publicly owned; 248 privately owned but subsidized, and 286 completely private (Consorci d'Educació de Barcelona, 2015). Usually schools have two groups per grade, that include elementary, primary and secondary education, with an average of 25 students per classroom (Generalitat de Cataluña, 2016).

These school buildings plus all the schools built and rehabilitated from the 1980`s are the majority of schools used at present. Most schools have a large multilevel building and a concrete construction system either on-site or precast and their roof structures were designed to withstand life weights of 200 kg/m^2, satisfying the Spanish Edification Technical Code (CTE) (RD 314/2006 (BOE, 2006)).

3. RESULTS

3.1. Results of application of the proposed methodology

3.1.1. Pre-selection criteria

Due to the amplitude of the whole sample, only those school buildings constructed during the 2000`s are considered for the present research. For the present study, the sample reported by Pons and Aguado (2012) has been updated to present, which includes 466 schools built in Catalonia, ie Barcelona and other towns. These schools have been filtered and guided by the aforementioned pre-selection criteria in section 2.1.1 of the present methodology, considering an area of 50-100m^2. In this way, the cases that have higher potential to fulfill all necessary requirements for RTG implementation, following the priority selection functions, is determined.

The 466 schools considered meet all the pre-selection criteria: comply technical building codes (security, …), and have a minimum free, flat, bearing capacity and sunny area (at least 50m^2, slope below 10% load capacity of at least 200kg/m^2 and minimum sun radiation of 1900-2000MJ/m^2 year or 13-14MJ/m^{2}day).

3.1.2. Selection necessities

The initial sample was analyzed through selection needs that include the architectural function and social participation. The first point of the Architectural function aspect refers to the location of schools within the boundaries of the city. After applying this point to the initial sample, 445 schools have been discarded; because they were located in towns near Barcelona and not within it.

The 21 schools that make up the reduced sample were contacted, in order to know the viewpoint of school staffs and parent's associations about the Architectural function and Social participation aspects. A brief semi-structured interview of 10 questions was applied to them (5 for school staffs and 5 for parent's associations) (Appendix, Table A.1). The questions for school staffs focused on the social and educational benefits of RTGs implementation. And for the parent`s associations focused in RTGs maintenance activities, environmental education and nutrition education were addressed. Nevertheless, only 11 schools showed interest in research and met all the selection needs of step two of the present methodology. So meetings were held with each of them for a technical visit.

3.1.2.1. Sample definition

After the application of the second stage of the present methodology, a final sample of 11 school was defined. Table 1 shows alphabetically the 11 schools that make up the study sample in the pre-selection stage. Each of them has been assigned a code (S1 to S11) to maintain study confidentiality.

Following the social character of the present research (economic criterion: 50-100m^2), the specific area of the RTG has been considered in each case depending on the available roof surface of the 11 schools. For cases S1 to S9 and S11 it was considered a RTG of 100m^2; for the case S10 it was on it possible 60m^2. In addition, because it is the first time that the methodology is applied, the sample should have some homogeneity; as it responds to the current characteristics and needs that take place in Barcelona.

Table 1. List of schools that make up the first sample (pre-selection criteria) and final sample (selection necessities).

		Final sample										
	School code	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Additional information	Built area (m^2)	5076	4626	2998	ND	3614	3128	2270	3309	3524	3818	4920
	Height (m)[a]	13	24	10	10	17	19	10	12	13	13	15
	Reinforced concrete structure	In situ	In situ	Precast	Precast	Precast	In situ	In situ	Precast	In situ	In situ	In situ
		Stage 1: Pre-selection criteria										
Legal & urban planning	CTE[b]	●	●	●	●	●	●	●	●	●	●	●
Economy	Roof maximum area available (m^2)	324	324	236	944	187	629	563	900	200	60	212
	Rooftop greenhouse size (m^2)	100	100	100	100	100	100	100	100	100	60	100
Agriculture	Free roof	●	●	●	●	●	●	●	●	●	●	●
	Solar radiation[c]	●	●	●	●	●	●	●	●	●	●	●
Technical	Flat roof[d]	●	●	●	●	●	●	●	●	●	●	●
	Roof resistant[e]	●	●	●	●	●	●	●	●	●	●	●
		Stage 2: Selection necessities										
Architectural function	Location	Sant Martí	Ciutat Vella	Sant Andreu	Sant Martí	Eixample	Ciudad Vella	Sarría-Sant Gervasi	Sant Martí	Gracia	Gracia	Sant Martí
	Kitchen &/or dining room	●	●	●	●	●	●	●	●	●	●	●
	Year of construction	2009	2012	2008	2012	2008	2013	2003	2008	2009	2009	2012
	Access to roof (s&E)[f]	●	●	●	●	●	●	●	●	●	●	●
Social participation	Sustainability project	●	●	●	●	●	●	●	●	●	●	●
	Scholar orchard	●	–	–	–	●	●	–	–	–	●	●
	School staff support	●	○	○	●	●	○	○	●	○	●	●
	parent's association support	●	○	○	●	●	○	○	●	○	●	●

[a] Respect to street
[b] Spanish Edification Technical Code (CTE) (RD 314/2006 (BOE, 2006))
[c] 1900-2000MJ/m^2 year or 13-14MJ/m^2day of solar radiation
d Slope: no greater than 10% (flat roof)
[e] Minimum load capacity of 200kg/m^2
[f] S&E: Stairs & Elevator
ND: No Data
– without scholar orchard
○ Interest in the initiative, minimum support

3.1.3 Sustainability analysis

- **Requirements tree**

The requirements tree (structured relevant parameters and weights) was mainly elaborated through seminars with multidisciplinary specialists. Due to its complexity, the elaboration was carried out in two sessions. In this way, difficulties in establishing weights or discrepancies among specialists could be avoided through a more organized process.

At the first seminar, requirements, criteria and indicators were defined by 10 specialists in the fields of agriculture, architecture, sustainability and urban planning. The conformation of the panel of experts was carried out following criteria of experience in the subjects previously mentioned and residing in the study city with an antiquity not less than 3 years. In order to find the most sustainable educational centers case for a RTG implementation in a Mediterranean compact city, exclusively the main economic (R1), environmental (R2) social (R3) and governance (R4) requirements, criteria and indicators were considered. No technical or functional indicators were taken into account to discriminate different alternatives because all alternatives fulfilled these requirements in a very similar way (no discrimination among them) since they are compulsory by construction standards. The resulting requirements tree was composed of 4 requirements, 12 criteria and 24 indicators.

During the second seminar a group of 20 multidisciplinary specialists were in charge of assigning the weights and value functions to the requirements tree. These specialists represented all parties involved from the Educational Department of Barcelona, City Council of Barcelona, City Agriculture Department and specialists from different universities of Barcelona: agronomists, architects, civil engineers, industrial engineers, and environmental engineers. For the conformation of this second panel, the same criteria of the first panel was used but adding the criterion of currently developing or working in educational centers in the city.

At this second seminar the first tree of requirements was reconsidered. All requirements, criteria and indicators were submitted to consensus due to the importance of their correct definition within the requirements tree. Later, weights were established in percentages; this process was carried out anonymously, in order not to condition the specialist's answers. Then, the average values chosen for each requirement, criteria and indicator were established using the Analytic Hierarchy Process (AHP) so reducing intricate decisions to a series of pairwise contrasts, and then sum up the results (Russo and Camanho, 2015).

Requirements	Criteria	Indicator	Explanation

And finally, the value functions for each of the indicators (trend, shape, …) were jointly agreed.

The main modifications made in the requirements tree during the second seminar were as follows. Three indicators were deleted (avoided impacts of food supply and consumption; avoided impacts of existing suppliers; and consumption transport and packaging). Three indicators were unified into one (Ventilation/Insulation/Thermal mass). And Maintenance impact indicator was added. Nevertheless, there was no significant variation (± 5%) in the percentage weights between the first and second meeting. The final result was a requirements tree integrated by 4 requirements, 11 criteria and 22 indicators. Table 2 shows the final tree with the specific characteristics of each indicator.

Table 2. Final requirements tree (with weights assignation) developed for the study case.

R1) Economic (30%)	C1) Investment (45%)	I1) Existing roof and building adaptation cost (50%)	Cost in € including the preparation (floor, structure, roof, foundation and services redesign and reinforcement if needed). Related to the roof surface.
		I2) RTG equipment and installation cost (30%)	Cost in € considering the type of RTG and its equipment a constant for all schools. So this cost will depend on the surface of the RTG.
		I3) Disassembly cost (20%)	Cost in € including disassembling the RTG and rebuilding the roof and taking all construction and debris waste to a recycling plant. Related to the roof surface.
	C2) Operation costs (35%)	I4) Maintenance cost (60%)	Cost in € taking into account the type of RTG and its equipment a constant for all schools. The maintenance program will be very similar as well. So this cost will depend on the surface of the RTG.
		I5) Food production cost (40%)	Cost in € considering similar crops and agriculture strategy and taking into account the RTG surface, orientation and solar radiation.
	C3) RTG food production (20%)	I6) Savings in purchasing school food (70%)	Savings in points taking into account the average food production, the menu and the cost of the food saved that won't be necessary to buy.
		I7) Potential for commercial food (30%)	Potential of extra food production depending on the school food needs and the RTG production taking into account surface, orientation and solar radiation. In points.
R2) Environmental (25%)	C4) Site conditions (25%)	I8) Rainwater harvesting capacity (50%)	Surface of the school building's roofs which can harvest water in m^2.
		I9) Solar radiation (50%)	Levels of solar radiation received by the roof in MJ/m^2.
	C5) Infrastructure impacts (30%)	I10) Construction and installation impacts (50%)	Partial simplified LCA including CO_2 emissions, energy consumption and materials of the construction phase of the building.
		I11) Maintenance impacts (30%)	Partial simplified LCA including CO_2 emissions, energy consumption and materials of the maintenance phase of the building.
		I12) Disassembly impacts (20%)	Partial simplified LCA of the RTG end of life phase including disassembling the RTG and taking the unnecessary materials to a recycling point.
	C6) Passive energy improvement (30%)	I13) Ventilation / Insulation /Thermal mass (100%)	Ventilation, insulation and thermal mass possibilities based on the the surface of the RTG in m^2. The type of RTG and its equipment are considered constant for all schools.
	C7) Active energy savings (15%)	I14) Potential for future thermal exchange (100%)	Potential for future thermal exchange considering existing heating air systems and pipes. The type of building heating system and existing services gallery and air conducts are taken into account. In points.
R3) Social (30%)	C8) School involvement (50%)	I15) Affinity to school main educational Project/s (50%)	Potential contribution to students' learning process By assessing if school educational main project takes into account children's participation potential and scientific education. In points.
		I16) Involvement in food education (30%)	Existing and planned future activities within school hours and lunch time involved in food education and nutritional improvements assessment. In points.
		I17) School menu model & nutrition quality (20%)	Nurition quality considering if the menu is balanced, nutritious, culturally appropriate and local. In points.
	C9) Families involvement (35%)	I18) Families acceptance potential (40%)	Potential of families acceptance considering families awareness of the benefits and potential of an RTG in relation to the education of children. In points.
		I19) Families knowledge contribution potential (30%)	Potential of families transmitting knowledge to school and vice versa. In points.
		I20) Families RTG multiuse potential (30%)	Potential of families recognizing the variety of potential uses and benefits a rooftop greenhouse can provide. In points.
	C10) Architectural integration (15%)	I21) Architectural integration possibilities (100%)	Aesthetic compatibility between the school building and RTGs. In the least compatible cases the RTG will be considered to be hided. In points.

R4) Governance (15%)	C11) Participation potential (100%)	I22) School staff and parent`s association acceptance & contribution potential (100%)	Potential acceptance and contribution willigness by school staff and parent`s associations based on interviews. In points.

- **Quantification of the indicators and value functions**

Table 3 presents the units value function shapes and sources for each indicator. Various scientific publications and information from school websites and Barcelona City Council were used for indicators I1 to I18. The values extracted from these sources were adapted to the different RTGs that were proposed for each school indicated in Table 1. On the other hand, the quantification of indicators from I19 to I22 was done through fieldwork and interviews. For all indicators evaluated by means of points, a scale of rising intensity was used graded as follows: nil or low, 0 points; medium 1 point; high 2 points; and very high 3 points; all of which were previously defined in the aforementioned seminars.

In this study, value functions are based on MIVES methodology, referenced, among others, by (Aguado et al., 2006; Viñolas et al., 2009). Functions have different shapes and are classified in: Decrease lineally (DL), Increase lineally (IL), Increase convexly (ICx) and Increase concavely (ICv) (although other options are possible in MIVES, as “S” shapes). The parameters and shape of value functions can be consulted in Viñolas, (2010).

Table 3. Units, value function shapes and sources of indicators.

Indicator	Unit	Shape	Source
I1. Existing roof and building adaptation cost	€/m^2	DL	Sanyé-Mengual, et al.,(2015)
I2. RTG equipment and installation cost	€/m^2	DL	Sanyé-Mengual, et al.,(2015)
I3. Disassembly cost	€/m^2	DL	Sanyé-Mengual, et al.,(2015)
I4. Maintenance cost	€/m^2	DL	Sanyé-Mengual, et al.,(2015)
I5. Food production cost	€/m^2	DL	Sanyé-Mengual, et al.,(2015)
I6. Savings in purchasing school food	Points	IL	Nadal et al., (2017) Sanyé-Mengual, et al., (2015)
I7. Potential for commercial food	Points	ICx	Nadal et al., (2017) Sanyé-Mengual, et al., (2015)
I8. Rainwater harvesting capacity	m^2	IL	Nadal et al., (2017)
I9. Solar radiation	Points	IL	City council of Barcelona
I10. Construction and installation impacts	Points	DL	Sanyé-Mengual, et al.,(2015)
I11. Maintenance impacts	Points	DL	Sanyé-Mengual, et al.,(2015)
I12. Disassembly impacts	Points	DL	Sanyé-Mengual, et al.,(2015)
I13. Ventilation / Insulation /Thermal mass	m^2	IL	Nadal et al., (2017)
I14. Potential for future thermal exchange	Points	ICx	Nadal et al., (2017)
I15. Affinity to school main educational Project/s	Points	IL	Schools website
I16. Involvement in food education	Points	ICv	Schools website
I17. School menu model & quality nutrition	Points	ICv	Schools website
I18. Families acceptance potential	Points	ICv	Parent’s association interview
I19. Families knowledge contribution potential	Points	ICv	Parent’s association interview

I20. Families RTG multiuse potential	Points	ICv	Parent's association interview
I21. Architectural integration possibilities	Points	IL	City council of Barcelona
I22. School staff and parent`s association acceptance & contribution potential	Points	ICv	schools staff and parent's association interviews

DL: Decreasing Lineal IL: Increase Lineally ICx: Increasing Convexly ICv: Increasing Concavely

3.1.4. Sensibility analysis and selection of the best alternative

Table 4 presents the non-dimensional values for the 11 school alternatives of this present study case. The real values (before the value function application) are shown in Appendix, Table A.2. Table 4 shows some indicators and criteria that only discriminate part of the alternatives. The reason is that the schools studied share many similar characteristics among them, such as location, school projects, building materials among others.

Furthermore, I1, I2, I4 and I5 (included in Investment and Operation costs criteria, inside Economic requirement) and I8, I10 and I13 (included in Site conditions, Infrastructure impacts and Ventilation/Insulation/Thermal mass criteria, inside Environmental requirements), do not discriminate between the school alternatives of this present study case. Contrary to this, I18 and I20, belonging to the Social requirement, are the indicators that most discriminate because the values of the cases studied present greater variability. MIVES models can be adapted more specifically to each study case by selecting exclusively the most discriminating indicators of each case . Nevertheless, the present research project has developed a more general model that could be applied to future samples within this study case boundaries and, therefore, some of the indicators that are not discriminative for these 11 schools would be discriminative for school cases of the following years.

Table 4. Criteria non-dimensional values for the 11 school alternatives.

		Indicator	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Requirements	Economic	I1. Existing roof and building adaptation cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		I2. RTG equipment and installation cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		I3. Disassembly cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.00
		I4. Maintenance cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		I5. Food production cost	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		I6. Savings in purchasing school food	0.33	0.67	0.33	0.33	0.33	1.00	0.67	0.33	0.33	0.33	0.33
		I7. Potential for commercial food	0.00	0.00	0.00	1.00	0.00	0.13	0.13	1.00	0.00	0.00	0.00
	Environmental	I8. Rainwater harvesting capacity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		I9. Solar radiation	1.00	1.00	1.00	1.00	0.50	1.00	0.50	1.00	1.00	0.75	1.00
		I10. Construction and installation impacts	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
		I11. Maintenance impacts	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
		I12. Disassembly impacts	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.67	0.33
		I13. Ventilation / Insulation /Thermal mass	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		I14. Potential for future thermal exchange	0.13	0.00	1.00	0.13	0.13	1.00	0.00	1.00	0.13	0.00	1.00
	C ⁝	I15. Affinity to school main educational Project/s	0.67	0.33	0.33	0.67	0.33	1.00	0.33	0.33	0.67	0.33	0.33

		I16. Involvement in food education	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
		I17. School menu model & quality nutrition	0.67	0.67	0.91	1.00	0.91	1.00	1.00	0.80	0.80	0.91	0.91
		I18. Families acceptance potential	0.00	0.80	0.00	1.00	0.49	0.00	0.00	0.49	0.00	0.91	0.67
		I19. Families knowledge contribution potential	0.49	0.80	0.00	1.00	0.91	0.00	0.00	0.00	0.00	1.00	0.49
		I20. Families RTG multiuse potential	0.49	0.67	0.00	1.00	0.80	0.00	0.00	0.91	0.00	0.91	0.80
		I21. Architectural integration possibilities	0.67	0.33	1.00	0.67	0.67	1.00	0.33	1.00	0.67	0.33	1.00
	Governance	I22. School staff and parent`s association acceptance & contribution potential	1.00	0.61	0.00	1.00	1.00	0.00	0.84	1.00	0.84	1.00	1.00
Global sustainability index			0.48	0.44	0.33	0.59	0.49	0.42	0.39	0.55	0.43	0.54	0.60

Aggregating these results, it is possible to obtain the global sustainability index for each school alternative. These indexes are shown in Fig. 3 and Fig. 4.

In Fig. 3 it can be noted that, in accordance with this model, S11 is the best option for the implementation of a RTG, with a global sustainability index of 0.60 (the highest one). Contrarily, S3 is the option with the lowest index of sustainability (0.33); so it is the worst option for the implementation of a RTG. The difference between the values obtained in S11 and S3 have a difference of 45%, but this depends on the indicators finally selected. For this case, social (R3) and governance (R4) requirements are the key differences between the best and worst case for the implementation of a RTG (S3 has null values in both of them).

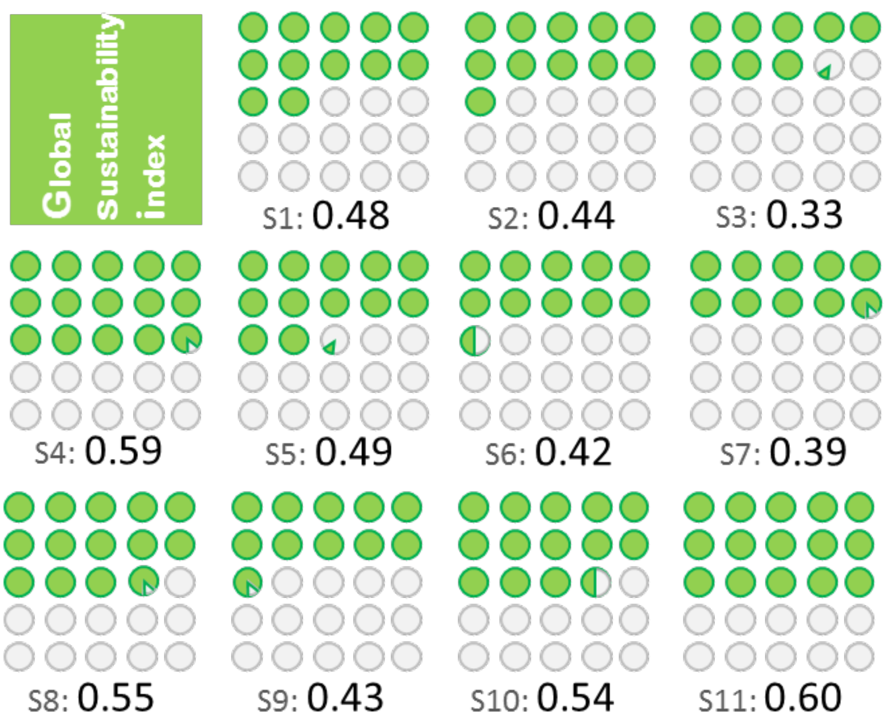


Fig 3. Global sustainability index values obtained for each school alternative.

To delve into the overall result of sustainability indexes it is necessary to analyze the results grouped by requirements. For this, Fig. 4 highlights the following:

- The three school with the highest values obtained (S11, S4 and S8) have a similar relationship in terms of the values for the 4 requirements, contrary to what happened in S3, S6 and S7 cases (considered the lowest options for RTG development).
- The Economic requirement (R1) presented the lowest sustainability values in all cases, not exceeding ever the normalized index of 0.09.
- The Environmental requirement (R2) is the second requirement that achieves the highest standardized sustainability indexes in all cases, because in all of them they have some project or initiative in favor of sustainability (e.g. Agenda 21, Green school, ISO 14000 and others).
- The Social requirement (R3) reached high normalized indexes (0.22) in cases S4 and S11, positioning them as the cases with the greatest potential for the implantation of the RTG and creating a remarkable difference with the other cases analyzed. However, there are considerable variations from one case to the next. For example, S11 has a value of 0.22 and S7 only 0.07.
- Governance (R4) is the most uniform requirement in almost all schools with a value of 0.15 of the normalized index, with the exception of cases S3 and S6 in which it was zero, because in these cases the support of the school staff and parent`s association was insipient or not relevant.

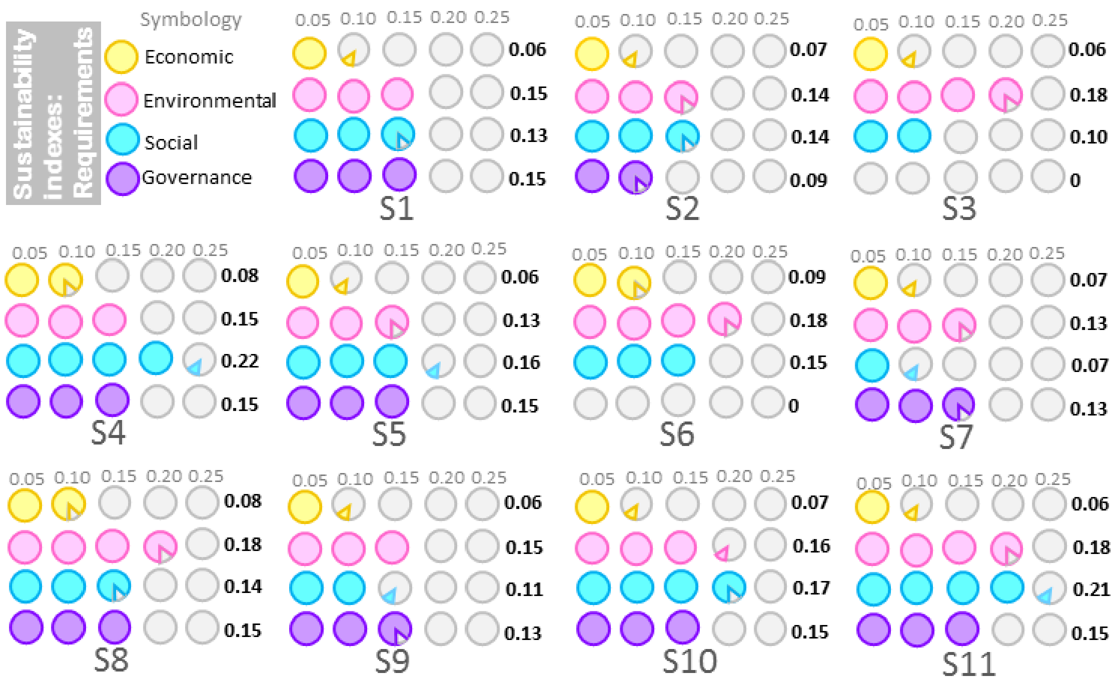


Fig. 4. Sustainability indexes grouped by requirements and derived from the sustainability analysis.

The indicator I22 School staff and parent`s association acceptance & contribution potential is the indicator with the highest influence in the sustainability index definition and results obtained. An important reason for this is that I22 has a weight of 100% within C11 and C11 has also a weight of 100%. That is, despite the fact that the Governance requirement has the lowest weight compared to the other three requirements, the fact of having only one criterion and one indicator makes the indicator to be individually the most important of all them. In this way, if I22 is compared in case S11 (with the highest sustainability index) and in S3 (with the lowest sustainability index), a difference of 100% is obtained. Therefore, for the present study, R4 (Governance) in the 11 cases, defines the results obtained in the global sustainability index. This indicates that the best case must include all the requirements and strive to balance between them. However, it also means that a sensitivity analysis is essential in order to assess properly the results obtained.

4. DISCUSSION

4.1. Sensitivity analysis

In addition to the scenario analyzed in the study case (scenario 1) described in Section 3.1, four different extreme scenarios have been assessed. These additional cases focus on each of the four requirements by giving a weight of 70% to this main requirement and

10% to the other three requirements. These cases are: Economic scenario (scenario 2); environmental scenario (scenario 3); social scenario (scenario 4) and governance social scenario (scenario 5).

Fig. 5 shows the results for the four extreme scenarios. Cases S4 and S11 stand out among the results S4 has a score of 0.40 for scenario 2 (economic) and 0.86 for scenario 4 (social). And for scenarios 3 and 5 (environmental and governance) case S11 presents the highest sustainability indexes with 0.65 and 0.86 respectively. These results are similar to those obtained in scenario 1 (case study) in which cases 11 and S4 presented the two highest sustainability indexes of the whole sample.

On the contrary, S3 presents the lowest indexes (0.23, 0.31 and 0.12) for scenarios 2, 4 and 5 (economic, social and governance) and S7 is the lowest for scenario 3 (environmental) with a value of 0.31. Similar to the cases with the highest values, the results of S3 and S7 coincide with those obtained in scenario 1 (case study) in which they presented the lowest sustainability indexes.

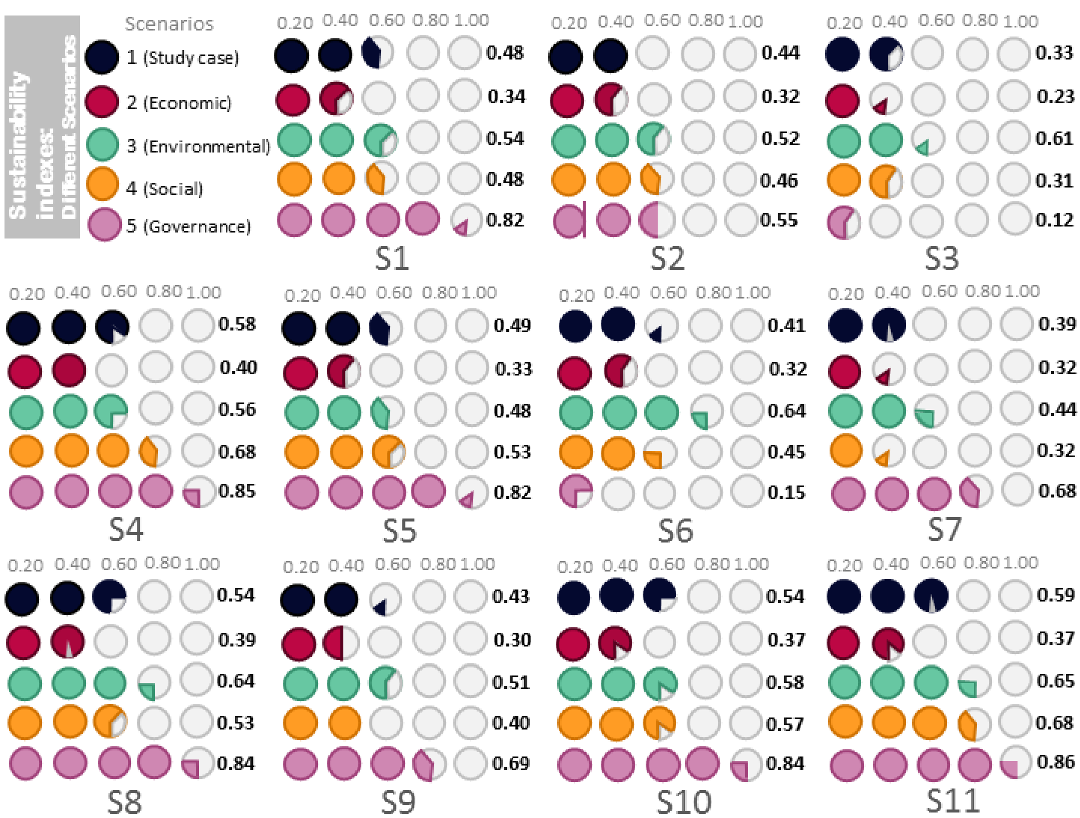


Fig. 5. Sustainability indexes obtained for the different scenarios considered in the sensitivity analysis.

S11 obtained the highest sustainability indexes in 3 out of the 5 scenarios (four extreme scenarios and the case study) and in contrast S3 obtained the lowest values in 4 out of the 5 scenarios. This reinforces the results obtained in the case study (Section 3.1) and shows that S11 is the best of the eleven options considered for the implementation of the rooftop greenhouse.

4.2. Methodology proposal outcomes

Through the analysis of a case study in Barcelona, it was possible to validate the application of the present methodology. Through its use, it is possible to propose recommendations to implement or improve sustainability strategies in schools in compact cities; key points to achieve a circular economy due to its reach and leadership within society.

The present method is a basic approach and it is necessary to make adaptations for its use in a different area, country or context. Specifically, these changes must be performed in stage 1 and 3.

- In stage 1, legal & urban planning and economy criteria must be updated depending on the area in which the study is developed.
- In stage 3, weights allocation must be as reliable and objective; must be based on scientific-technical reasons and specialist use panels of multidisciplinary specialists that support the decision. For the weights selection of the quantitative parameters it is better to use indicators and units based on well-known practices or international units.
- In addition, for the qualitative parameters it is recommended to use levels or scales that go from 0 to 5 or 10 (or alternatively from 0 to 100), in order to facilitate the quantification and weights definition.

5. CONCLUSIONS AND FUTURE WORK

The objective defined in this research project, is to generate an assessment tool capable of choosing the best school building for the location of a sustainable rooftop greenhouse. This model has enabled to evaluate the sustainability index of each alternative, through the value functions and the weights assigned to the different requirements, criteria and indicators of the requirements tree.

The four main advantages of the use of this methodology are as follows:

- Has proven to be an objective, adaptable tool with a multidisciplinary character, for decision-making in the field of sustainability in priority areas of cities around the world -schools- through the use of urban agriculture in the rooftop greenhouse modality. In addition to supporting the goal 11, of the Sustainable development goals promoted by the United Nations: Make cities inclusive, safe, resilient and sustainable.
- The methodology has a social approach, due to the educational character and social cohesion that schools represent within society. This approach is reinforced by using an area between 50-100m^2 in the pre-selection principles - step 1-; in social and governance requirements (R3 and R4) in the decision tree - step 3; in the interviews with the social actors (schools staff and parent`s association) and the two panels of multidisciplinary specialists - step 3.
- This viable and reliable alternative minimizes the subjectivity in the process to evaluate, compare and select the best alternative for the potential implementation of RTGs in schools through the measurement of a global sustainability index.
- The use of four stages, diverse tools -among them MIVES- and a sensitivity analysis facilitates its application, without its objectivity being reduced.

In order to evaluate the proposed methodology, 11 Barcelona schools were analyzed, highlighting:

- As a result of the social approach of the methodology, S11 case was the best alternative for the implementation of a rooftop greenhouse (highest sustainability index; 0.60), because it presented the support of the school staff and the parent`s association, in addition to being originally designed to house a school garden within their facilities. In the opposite sense, S3 case, only reached 0.33 in the sustainability index, in part because of the lack of a school garden and the low interest of social actors
- In this study case, the main constraints for the development of greenhouses in schools are low interest by some social actors and competition for rooftop use (playground vs. greenhouse).

It should be noted that these results only refer to the case study analyzed, so in other case studies different results have to be obtained, because the focus, character, weights, panels and others will be or may be different.

For future works, the proposed method establishes an advance in terms of sustainability assessment in urban agriculture projects or initiatives by government, managers, architects, engineers, urban planners and other professionals and in the implementation of the concept of urban sustainability, because the method ensures objectivity and clarity in the result. The method and the tools used in the present research can also be useful to establish the basis for succeeding analysis of other urban agriculture alternatives in cities.

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Appendix A.

Table A.1. List of questions that were applied in interviews with parent`s associations and schools staff.

Subject of the interview	Questions
Parent´s association	1. Would you participate in related educational activities? 2. Would you encourage parents with knowledge about agriculture and external professionals to do teaching activities at school? 3. How do you see the option of inviting parents to do adult learning activities in the greenhouse on urban agriculture at school? 4. Would you participate in the cultivation and maintenance during the school year and during holiday periods? 5. Would you be in favor of building a greenhouse on one of the roofs without the current use of the school to use it for educational, food production and improvement of comfort in your school? And with what conditions?
School staff	1. Would you be in favor or against building a greenhouse in one of your current unused covers to be used for educational purposes, food production and the comfort improvement of your school? Why? 2. What is the main educational project of your school? 3. Do you have educational activities related to food education and nutritional improvements? In which courses? How many hours? 4. Do you have educational activities related to food education and nutritional improvements during your lunch breaks? How many hours 5. Which school menu model do you have? What nutritional quality do foods have in the dining room of the school?

Table A.2. Values of the parameters involved in the assessment of each indicator.

Indicator	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S12
I1. Existing roof and building adaptation cost	€/m^2	**539**	539	539	539	539	539	539	539	539	323.4	539
I2. RTG equipment and installation cost	€/m^2	**502**	502	502	502	502	502	502	502	502	301.2	502
I3. Disassembly cost	€/m^2	**269.5**	269.5	269.5	269.5	269.5	269.5	269.5	269.5	269.5	161.7	269.5
I4. Maintenance cost	€/m^2	**651**	651	651	651	651	651	651	651	651	390.6	651
I5. Food production cost	€/m^2	**64.35**	64.35	64.35	64.35	64.35	64.35	64.35	64.35	64.35	38.61	64.35
I6. Savings in purchasing school food	Points	**1**	2	1	1	1	3	2	1	1	1	1
I7. Potential for commercial food	Points	**1**	1	1	3	1	2	2	3	1	0	1
I8. Rainwater harvesting capacity	m^2	**100**	100	100	100	100	100	100	100	100	60	100
I9. Solar radiation	Points	**4**	4	4	4	2	4	2	4	4	3	4
I10. Construction and installation impacts	Points	**3**	3	3	3	3	3	3	3	3	2	3
I11. Maintenance impacts	Points	**3**	3	3	3	3	3	3	3	3	2	3
I12. Disassembly impacts	Points	**2**	2	2	2	2	2	2	2	2	1	2
I13. Ventilation / Insulation /Thermal mass	m^2	**100**	100	100	100	100	100	100	100	100	60	100
I14. Potential for future thermal exchange	Points	**2**	1	3	2	2	3	1	3	2	1	3
I15. Affinity to school main educational Project/s	Points	**2**	1	1	2	1	3	1	1	2	1	1
I16. Involvement in food education	Points	**0**	0	0	0	0	0	0	0	0	0	3

I17. School menu model & quality nutrition	Points	**2**	2	4	5	4	5	5	3	3	4	4
I18. Families acceptance potential	Points	**0**	3	0	5	1	0	0	1	0	4	2
I19. Families knowledge contribution potential	Points	**1**	3	0	5	4	0	0	0	0	5	1
I20. Families RTG multiuse potential	Points	**1**	2	0	5	3	0	0	4	0	4	3
I21. Architectural integration possibilities	Points	**2**	1	3	2	2	3	1	3	2	1	3
I22. School staff and parent`s association acceptance & contribution potential	Points	**3**	1	0	3	3	0	2	3	2	3	3

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