Low-cost intelligent refurbishment of façades
A study of Barcelona public school building façades

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Thesis by compendium of publications
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Glossary

Term	Definition
Analytical hierarchy process	AHP is a method for organizing and analyzing complex decisions, using math and psychology [1].
Building-integrated photovoltaic	BIPV are photovoltaic materials that are used in parts of the building envelope such as the roof, skylights, or facades [2].
Building integrated solar thermal	BIST is defined as the "multifunctional energy facade" that offers a wide range of solutions in architectural design features of buildings' heating/cooling, hot water supply, power generation and simultaneously improvement of the insulation and overall appearance of buildings [3].
Circular economy	A circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible [4].
Cradle to cradle	Cradle-to-cradle is a biomimetic approach to the design of products and systems that models human industry on nature's processes, where materials are viewed as nutrients circulating in healthy, safe metabolisms [5].
Cradle to grave	'Cradle-to-grave' assessment considers impacts at each stage of a product's life-cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, and ultimately, disposal.
Cross consistency assessment	CCA serves as a check on the integrity and clarity of the concepts being employed, and allows us to identify and weed out all internally incompatible relationships in order to reduce the total problem space of the morphological field to a smaller, internally consistent solution space [6].
Crystallinity	Crystallinity can be defined as the degree of long-range structural order comprising a crystal lattice within a (solid) material [7].
Delphi	The Delphi method is a systematic and qualitative method of forecasting by collecting opinions from a group of experts through several rounds of questions. The Delphi method relies on experts who are knowledgeable about a certain topic so they can forecast the outcome of future scenarios, predict the likelihood of an event, or reach consensus about a particular topic [8].
Deterministic random bit generator	A random bit generator that includes an algorithm and (at least initially) has access to a source of randomness. The DRBG produces a sequence of bits from a secret initial value called a seed [9].
Differential scanning calorimetry	Differential scanning calorimetry is a thermoanalytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature [10].
Double skin façade	The DSF can be defined as a system of building consisting of two skins, or façades, placed in such a way that air flows in the intermediate cavity. The ventilation of the cavity can be natural, fan supported or mechanical. Apart from the type of the ventilation inside the cavity, the origin and destination of the air can differ depending mostly on climatic conditions, the use, the location, the occupational hours of the building and the HVAC strategy.
Do it yourself	DIY can be considered as a method of building, modifying, or repairing things by oneself without the direct aid of professionals or certified experts.
Electro-active façade	Also known as Electrochromic dynamic facade, which enables to control the amount of visible light and solar heat gain entering a space, over a large range that varies between 60 per cent and 1 per cent in visible light transmission and 0.40 to 0.05 in solar g-factor. The modulation of light and heat can be controlled through building automation system, or at the touch of a button, so as to dynamically adapt to the external climatic conditions and occupants' needs, with no moving parts [11].
Embodied carbon	Embodied carbon refers to the greenhouse gas emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials.
Embodied energy	Embodied energy refers to the consumed energy during the manufacturing, transportation, installation, maintenance, and disposal process of building materials.
Energy conversion efficiency	Energy conversion efficiency is the ratio between the useful output of an energy conversion machine and the input, in energy terms [12].
Experimental methodology	a system of scientific investigation, usually based on a design to be carried out under controlled conditions, that is intended to test a hypothesis and establish a causal relationship between independent and dependent variables [13].

Focus group	A focus group is a research method that brings together a small group of people to answer questions in a moderated setting. The group is chosen due to predefined demographic traits, and the questions are designed to shed light on a topic of interest [14].
General Morphology Analysis	GMA is a method for identifying and investigating the total set of possible relationships or "configurations" contained in a given problem complex. In this sense, it is closely related to typology analysis, although GMA is more generalized in form and has far broader applications [15].
Intelligent façade	An incorporating variable technology, which would amend itself to provide comfort conditions inside the building whatever the external environmental conditions, might be, in any particular building location [16].
ISO 4892-1:2016	ISO 4892-1:2016 provides information and general guidance relevant to the selection and operation of the methods of exposure. It also describes general performance requirements for devices used for exposing plastics to laboratory light sources. Information regarding performance requirements is for producers of artificial accelerated weathering or artificial accelerated irradiation devices.
ISO 4892-2:2013	ISO 4892-2:2013 specifies methods for exposing specimens to xenon-arc light in the presence of moisture to reproduce the weathering effects (temperature, humidity and/or wetting) that occur when materials are exposed in actual end-use environments to daylight or to daylight filtered through window glass.
ISO 527	The standards ISO 527-1 (general principles) and ISO 527-2 (test conditions for molding and extrusion materials) describe tensile testing on plastics.
Life cycle assessment	LCA is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service [17].
Life cycle costing	LCC is a technique used to estimate the total cost of ownership. It is a system that tracks and accumulates the actual costs and revenues attributable to cost object from its invention to its abandonment. It allows comparative cost assessments to be made over a specific period of time, taking into account relevant economic factors both in terms of initial capital costs and future operational and asset replacement cost [18].
Life cycle inventory	LCI is the methodology step that involves creating an inventory of input and output flows for a product system. Such flows include inputs of water, energy, and raw materials, and releases to air, land, and water [19].
Maximum tensile load	Maximum tensile load is the maximum stress that a material can withstand while being stretched or pulled before breaking [20].
MIVES	MIVES is a customizable and agile sustainable assessment model that enables overall assessment, comparison, and ranking of alternatives [21].
Multi-Criteria Decision-Making	MCDM is a research area that involves the analysis of various available choices in a situation or research area which spans daily life, social sciences, engineering, medicine, and many other areas [22].
Municipal Solid Waste	MSW, commonly known as trash, garbage, or rubbish, is a waste type consisting of everyday items that are discarded by the public. "MSW" also refer specifically to food waste, as in a garbage disposal.
Nominal group technique	NGT is defined as a structured method for group brainstorming that encourages contributions from everyone and facilitates quick agreement on the relative importance of issues, problems, or solutions [23].
Numerical methodology	Numerical analysis is the study of algorithms that use numerical approximation for the problems of mathematical analysis. It is the study of numerical methods that attempt at finding approximate solutions of problems rather than the exact ones [24].
Phase change materials	PCMs are able to absorb, store and release large amounts of latent heat over a defined temperature range when the material changes phase or state [25].
Photo bio-reactor panel	PBR panels refers to cultivation system of bioactive compounds for biofuels, pharmaceuticals, and other industrial uses, through absorbing solar light and carbon dioxide. PBR panels are transparent containers which create a controlled environment in buildings by controlling shading and energy consumption [3].
PRISMA	PRISMA is an evidence-based minimum set of items aimed at helping scientific authors to report a wide array of systematic reviews and meta-analyses. The PRISMA statement consists of a 27-item checklist and a 4-phase flow diagram [26].
Sensitivity analysis	Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system can be divided and allocated to different sources of uncertainty in its inputs [27].

Shear load	A shear load is a force that tends to produce a sliding failure on a material along a plane that is parallel to the direction of the force [28].
Sustainability	Sustainability consists of fulfilling the needs of current generations without compromising the needs of future generations, while ensuring a balance between economic growth, environmental care and social well-being.
Systematic review	A systematic review is a scholarly synthesis of the evidence on a clearly presented topic using critical methods to identify, define and assess research on the topic [29].
Tetra pak	Tetra Pak is a type of plasticized carton for milk, juice and other drinks, originally in the form of a tetrahedron but now primarily in the form of a rectangular cuboid [30].
Titanium Dioxide nanotechnology	TiO_2 are particles with diameters less than 100 nm has ability to block ultraviolet radiation while remaining transparent. It is in rutile crystal structure and coated with silica or/and alumina to prevent photocatalytic phenomena. The health risks of ultrafine TiO_2 is extremely low and it is considered safer than other substances used for ultraviolet protection. Surfaces of ultrafine TiO_2 in the anatase structure have photocatalytic sterilizing properties, which make it useful as an additive in construction materials, for example in antifogging coatings and self-cleaning windows [31].
Utility model	A utility model can be defined as a patent-like intellectual property right to protect inventions.
Value function	The value function of an optimization problem gives the value attained by the objective function at a solution, while only depending on the parameters of the problem [32].
Waste hierarchy	The Waste hierarchy is a tool used in the evaluation of processes that protect the environment alongside resource and energy consumption from most favorable to least favorable actions [33].

List of codes and abbreviations

Abbreviation	Relevant value
ARTS	Alkaline roasting of titania slag
BIPV	Building-integrated photovoltaic
BIST	Building integrated solar thermal
BM	Biomass
DSF	Double skin façade
DSPF	Double-skin perforated façade
EC	Embodied carbon
EE	Embodied energy
ETFE	Ethylene tetrafluoroethylene cushion
GHG	Greenhouse gas
GWP	Global warming potential
HP	Hydro-power
IF	Intelligent façade
LCA	life-cycle assessment
LCC	life cycle costing
MCDM	multi-criteria decision-making
PBR	photo bio-reactor
PCM	Phase change materials
PE	Piezoelectric
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
RS	Renewable system
SLR	Systematic literature reviews
SMA	Shape memory alloys
SPD	Suspended particle device
STCW	Solar thermal curtain wall
VAWT	Vertical axis wind turbines
VGS	Vertical green system
WG	Wind generator
WWR	Window to wall ratio
SEJ	Joules of solar energy
FU	Functional unite
kWp	Kilowatts peak
CU	Currency unit

TiO_2	Titanium Dioxide nanotechnology
CFD	Computational Fluid Dynamics
ISO	International Organization for Standardization
HDPE	High-density polyethylene
PET	Polyethylene terephthalate
CCA	Cross-Consistency Assessment
AC	Air conditioning
AHP	Analytic Hierarchy Process
PTFE	Polytetrafluoroethylene
Apv	Acrylic paint + varnishing
Ppv	Poster paint + varnishing
CFD	Computational Fluid Dynamics
wIser	Waste-based Intelligent Solar-control-devices for Envelope Refurbishment
LCI	Life cycle inventory
DSC	Different scanning calorimetry
IFL	Intelligent Façade Layer
nZeb	Nearly Zero-energy buildings
PC	PolyCarbonate
Do sensor	Dissolved Oxygen Sensor
SS	Stainless Steel
MIVES	Integrated Value Model for Sustainable Assessment (Modelo Integrado de Valor para una Evaluacion ´ Sostenible)
GMA	General Morphology Analysis
GS_k	Global sustainability index
LED	Light-Emitting Diodes
DCV	Decreasing Concave
DL	Decreasing Lineal
ICX	Increasing Convex
IL	Increasing Lineal
N/A	Not Applicable
UA	Unexpected Alternative
UV	Ultraviolet
DSC	Differential scanning calorimetry
TB	Tetra brik sheet
Tp	Polyamide threat
HMA	Transparent hot melt adhesive
PP	Polypropylene
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
NL	Neutral location
DSC	Differential scanning calorimetry

Abbreviations for Equations

Abbreviation	Relevant value
A	The response value to Xmax
ki	Value that comes closer to the ordinate of the curve inflection point
Xalt	Each response to the indicator value function
Xm = Xmax	The maximum abscissa value considered for decreasing indicators
Xm = Xmin	The minimum abscissa value considered for increasing indicators
Ci	Value that closer to the abscissa value of the curve inflection point
B	Parameter that maintains the function within the 0 to 1 range
$SI_{Ri,k}$	Requirements satisfaction index
$CI_{Ri,k}$	Criteria satisfaction index
$V_{i,k}$	Value from the value function satisfaction

Abstract

Due to the fact that construction, maintenance, and operation of buildings consume almost 40% of global energy today, architects play a major role in the reduction of world energy consumption. **Building's façades can have a significant and measurable impact on the economic, environmental, and social performances by edifices, and their retrofit is seen as a key solution to the problem of today's aging building stock.** Concerning overheating and the potential loss of internal heat, transparent parts of the building façade have a large effect on the building's energy consumption. Within this context, the use of intelligent systems on architecture envelopes can fulfill contemporary demands as promising solutions regarding energy efficiency, emissions, or the degree of visual contact in building environments.

In Spain, boom periods of construction combined with typical building styles of each period, have resulted in a large stock of aging educational buildings at risk of structural vacancy and obsolescence. Despite their lack of insulation, high air infiltration, and solar gain, many such edifices from the 1970s-1980s are still in use today. Moreover, **the majority of today's buildings will still be in use in 2050** based on the Spanish edifices' annual replacement rate of 3% according to the European Commission.

The main objective of this Ph.D. thesis is to analyze, develop and promote intelligent services to existing façades to optimize these buildings' economic, environmental, and social sustainability performances through a holistic and innovative sustainability assessment model.

To do so, the first phases of this thesis, the author carried out a deep **documental investigation** on more than 800 research articles regarding **intelligent façade systems**, advancements in material engineering, user demands, automations, and their sustainability performance following the preferred reporting items for **systematic reviews and meta-analyses reporting standards**.

Based on the results from preliminary investigations, **different low-cost and environmental-friendly dynamic façades have been prototyped in the context of the Spanish public schools targeting pupils' academic progress through optimizing the lighting and thermal comfort levels**. These **prototypes have been developed by employing municipal solid waste materials during participatory workshops with school pupils**. This concept is expected to promote awareness and better management of our society's critical waste generation by returning waste to the **reusing cycle**.

From the data collected, researchers found that **intelligent façade design and application result from a complex decision-making process.** The cost and long-term nature of the investment mean that the façade decision is strategic. Accordingly, the next phase examined the actuality of intelligent façade projects in practice through conducting in-depth exploratory methodologies and tools for analyzing, evaluating, and designing among the incorporation of interdisciplinary experts in the topic. Finally, the last phase experimentally monitored and tested the developed prototypes and other test samples of various waste items.

The findings show that the process of **façade retrofit** that fulfills the school building functioning, energy performance, emissions, costs, and appearance, **requires the realm of the profession**. The members involved in the retrofitting projects of public primary school buildings mainly had to make initial façade design decisions based on ideas resulting from cognition and drawing on experience.

This thesis and its subsequent conceptual framework provide a **new overview of waste-based construction materials and their introduction to developing intelligent façade technologies,** through scientific indexes that can be useful for occupants, builders, architects, and policymakers to have a good understanding of the potential contributions that intelligent façades provide.

Keywords: Intelligent façades; Public primary schools; Retrofit; Waste reuse; Workshop; Comfort; Academic progress; Sustainability assessment;

Resumen

La construcción, mantenimiento y funcionamiento de edificios consumen casi el 40% de la energía actual, así que los arquitectos tienen un papel fundamental en la reducción del consumo energético. **Las fachadas pueden tener un impacto significativo y medible en el rendimiento económico, medioambiental y social de edificios, y su rehabilitación se considera una solución clave para el problema del envejecimiento del parque inmobiliario actual.** En referencia al sobrecalentamiento y posible pérdida de calor interno, las oberturas de las fachadas tienen un gran efecto en el consumo energético del edificio. Así, se pueden satisfacer las demandas actuales con el uso de sistemas inteligentes en envolventes arquitectónicas, como soluciones prometedoras en eficiencia energética, emisiones o grado de contacto visual en entornos construidos.

En España, los periodos de auge de la construcción han dado lugar a numerosos edificios educativos envejecidos que corren el riesgo de quedar obsoletos. A pesar de su falta de aislamiento, problemas de infiltraciones de aire y ganancia solar, muchos de estos edificios de los años 70-80 siguen en uso hoy en día. Además, **la mayoría de estos edificios seguirán en uso en 2050,** si se tiene en cuenta que la tasa de sustitución anual de los edificios españoles es del 3%, según la Comisión Europea.

"El objetivo principal de esta tesis doctoral es analizar, desarrollar y promover servicios inteligentes para fachadas existentes con el fin de optimizar las prestaciones de sostenibilidad económica, medioambiental y social de sus edificios a través de un modelo holístico e innovador de evaluación de la sostenibilidad".

Para ello, las primeras fases de esta tesis investigaron en profundidad más de 800 artículos científicos sobre **sistemas de fachadas inteligentes**, avances en la ingeniería de materiales, demandas de los usuarios, automatizaciones y su rendimiento global en materia de sostenibilidad, siguiendo los ítems preferidos para **la presentación de informes de revisiones sistemáticas y meta-análisis.**

Considerando investigaciones preliminares, **se han creado prototipos de fachadas dinámicas de bajo coste y respetuosas con el medio ambiente en el contexto de los colegios públicos españoles, cuyo objetivo es el progreso académico de los alumnos mediante la optimización de los niveles de iluminación y confort térmico.** Estos prototipos han sido **desarrollados con residuos sólidos municipales durante talleres participativos con alumnos de escuelas.** Se espera que este concepto promueva concienciación crítica y una mejor gestión de los residuos de nuestra sociedad, devolviendo **los residuos al ciclo de reutilización.**

A partir de los datos recogidos, se ha comprobado que **el diseño y aplicación de fachadas inteligentes son fruto de un complejo proceso de toma de decisiones**. El coste y naturaleza de la inversión a largo plazo hacen que la decisión sobre la fachada sea estratégica. La siguiente fase examinó la actualidad de proyectos de fachadas inteligentes en la práctica mediante metodologías y herramientas exploratorias para el análisis, evaluación y diseño en profundidad, incorporando expertos interdisciplinarios. La última fase supervisó y probó experimentalmente los prototipos desarrollados.

Los resultados muestran que el proceso de **rehabilitación de fachadas** que cumple en funcionamiento, rendimiento energético, emisiones, costes y apariencia de la escuela, **requiere el ámbito de la profesión**. Los participantes en la rehabilitación de escuelas de primaria tuvieron que tomar principalmente decisiones iniciales sobre el diseño de la fachada basadas en ideas resultantes de la cognición y experiencia.

Esta tesis y su marco conceptual proporcionan **una nueva visión de la construcción basada en residuos y su introducción en el desarrollo de tecnologías de fachadas inteligentes,** a través de índices científicos que pueden ser útiles para que ocupantes, constructores, arquitectos y responsables políticos tengan una buena comprensión de las contribuciones potenciales que proporcionan las fachadas inteligentes.

Palabras clave: Fachadas inteligentes; Escuelas primarias públicas; Reacondicionamiento; Reutilización de residuos; Taller; Comodidad; Progreso académico; Evaluación de la sostenibilidad.

Resum

La construcció, el manteniment i funcionament de edificis consumeixen quasi el 40% de l'energia actual, així que els arquitectes tenen un paper fonamental en la reducció del consum energètic. **Les façanes poden tenir un impacte significatiu i mesurable en el rendiment econòmic, mediambiental i social dels edificis, i la rehabilitació es considera una solució clau per al problema de l'envelliment del parc immobiliari actual**. Pel que fa al sobreescalfament i possible pèrdua de calor interna, les parts transparents de les façanes tenen un gran efecte en el consum energètic de l'edifici. Així, es poden satisfer les demandes actuals amb l'ús de sistemes intel·ligents a envolupants arquitectòniques, com ara solucions prometedores en eficiència energètica, emissions o grau de contacte visual en entorns construïts.

A Espanya, els períodes d'apogeu de la construcció han donat lloc a nombrosos edificis educatius envellits que corren el risc de quedar obsolets. Tot i la manca d'aïllament, problemes d'infiltracions d'aire i guany solar, molts d'aquests edificis dels anys 70-80 segueixen en ús avui dia. A més a més, **la majoria d'aquests edificis continuaran en ús el 2050**, si es té en compte que la taxa de substitució anual dels edificis espanyols és del 3%, segons la Comissió Europea.

"L'objectiu principal d'aquesta tesi doctoral és analitzar, desenvolupar i promoure serveis intel·ligents per a façanes existents per optimitzar les prestacions de sostenibilitat econòmica, mediambiental i social dels seus edificis mitjançant un model holístic i innovador d'avaluació de la sostenibilitat".

Per això, les primeres fases d'aquesta tesi, van investigar en profunditat més de 800 articles científics sobre **sistemes de façanes intel·ligents**, avenços en l'enginyeria de materials, demandes dels usuaris, automatitzacions i el seu rendiment global en matèria de sostenibilitat, seguint els ítems preferits per a **la presentació d'informes de revisions sistemàtiques i metaanàlisi**.

Considerant investigacions preliminars, **s'han creat prototips de façanes dinàmiques de baix cost i respectuoses amb el medi ambient en el context dels col·legis públics espanyols, l'objectiu dels quals és el progrés acadèmic dels alumnes mitjançant l'optimització dels nivells d'il·luminació i confort tèrmic**. Aquests prototips han estat **desenvolupats amb residus sòlids municipals durant tallers participatius amb els alumnes d'escoles**. S'espera que aquest concepte promogui conscienciació crítica i una millor gestió dels residus de la nostra societat, tornant **els residus al cicle de reutilització**.

A partir de les dades recollides, s'ha comprovat que **el disseny i aplicació de façanes intel·ligents són fruit d'un complex procés de presa de decisions**. El cost i naturalesa de la inversió a llarg termini fan que la decisió sobre la façana sigui estratègica. La fase següent va examinar l'actualitat dels projectes de façanes intel·ligents a la pràctica mitjançant metodologies i eines exploratòries per a l'anàlisi, avaluació i disseny en profunditat amb la incorporació d'experts interdisciplinaris. La darrera fase va supervisar i provar experimentalment els prototips desenvolupats.

Els resultats mostren que el procés de **rehabilitació de façanes** que compleix en funcionament, rendiment energètic, emissions, costos i aparença de l'escola **requereix l'àmbit de la professió**. Els participants a la rehabilitació d'edificis de primària van haver de prendre principalment decisions inicials sobre el disseny de la façana basades en idees resultants de la cognició i experiència.

Aquesta tesi i el seu marc conceptual proporcionen **una nova visió de la construcció basada en residus i la seva introducció en el desenvolupament de tecnologies de façanes intel·ligents**, a través d'índexs científics que poden ser útils per a què ocupants, constructors, arquitectes i responsables polítics tinguin una bona comprensió de les contribucions potencials que proporcionen les façanes intel·ligents.

Paraules clau: Façanes intel·ligents; Escoles primàries públiques; Recondicionament; Reutilització de residus; Taller; Comoditat; Progrés acadèmic; Avaluació de la sostenibilitat.

خلاصه

با توجه به اینکه امروزه ساخت، نگهداری و بهره برداری از ساختمان ها در حدود ۴۰ درصد از انرژی کل را مصرف می کند، معماران نقش عمده ای در کاهش این مصرف را دارند. نماهای ساختمان می توانند تأثیر قابل توجه بر عملکرد اقتصادی، زیست محیطی و اجتماعی ساختمان ها و شهرها داشته باشد و بهبود سازی آن به عنوان یک راه حل کلیدی برای مشکل موجودی ساختمان های قدیمی تلقی می شود. با توجه به ایجاد گرمای بیش از حد محیط داخلی و یا حدر رفتن بالقوه گرمای داخلی، قسمت های شفاف نمای ساختمان تاثیر زیادی بر مصرف انرژی دارند. بنابراین، استفاده از سیستم‌های هوشمند در معماری نماها می‌تواند خواسته‌های معاصر را به عنوان راه‌حل‌های امیدوارکننده در مورد بهره‌وری انرژی، انتشار گازهای گلخانه‌ای یا درجه تماس بصری در محیط‌های ساخته شده برآورده کند.

در اسپانیا، دوره‌های رونق ساخت و ساز همراه با سبک‌های ساختمانی معمولی در هر دوره، منجر به انبار بزرگی از ساختمان‌های آموزشی قدیمی شده است که در معرض خطر تخلیه و فرسودگی قرار دارند. با وجود عایق بندی بسیار ضعیف و امکان نفوذ هوا و نور خورشیدی، بسیاری از این بناهای به جامانده از دهه ۷۰ تا ۸۰ هنوز در حال استفاده هستند. علاوه بر این، بر اساس نرخ جایگزینی سالانه ۳ درصدی ساختمان‌های اسپانیایی ، اکثر ساختمان‌های امروزی همچنان تا سال ۲۰۵۰ مورد استفاده قرار خواهند گرفت.

هدف اصلی این پروژه دکتری، تجزیه و تحلیل، توسعه و ترویج خدمات هوشمند به نماهای موجود برای بهینه سازی عملکرد پایداری اقتصادی، زیست محیطی و اجتماعی ساختمان ها از طریق مدل جدید و جامع ارزیابی پایداری می باشد.

برای انجام این هدف، فازهای اولیه این پروژه، بیش از ۸۰۰ مقاله تحقیقاتی در مورد سیستم های نمای هوشمند گسترده، پیشرفت در مهندسی مواد، خواسته های ساکنین، اتوماسیون ها و عملکرد پایدار جهانی آنها را توسط الگوهای بررسی های سیستماتیک و متاآنالیز مورد بررسی عمیق و جانع قرار داد.

بر اساس نتایج بررسی‌های اولیه، چندین نمای هوشمند جدید پایدار و کم‌هزینه و سازگار با محیط زیست در چارچوب مدارس دولتی اسپانیا که پیشرفت تحصیلی دانش‌آموزان را از طریق بهینه‌سازی روشنایی و آسایش حرارتی هدف قرار می‌دهند، نمونه‌سازی شده‌اند. این نمونه‌های اولیه توسط مواد زباله جامد شهری طی کارگاه‌های مشارکتی با دانش‌آموزان طراحی و نصب گردیدند. انتظار می رود این مفهوم با بازگرداندن زباله به چرخه استفاده مجدد، آگاهی و مدیریت بهتر تولید زباله های حیاتی جامعه ما را ارتقا دهد.

از داده های جمع آوری شده، مشخص شده است که فرایند طراحی، توسعه و نصب نمای هوشمند یک پروسه ی تصمیم گیری پیچیده و جامع هست. هزینه و ماهیت بلند مدت سرمایه گذاری به این معنی است که تصمیم برای توسعه نماهای هوشمند یک تصمیم استراتژیک است. بر این اساس، مراحل بعدی این پروژه با استفاده از روش ها و ابزارهای ارزیابی و طراحی و ادغام کارشناسان در این حوزه، پروژه نمای هوشمند برای بهبود سازی نماهای مدارس را به صورت واقعی در ۳ مدرسه در ایالت

کاتالونیا انجام داد. در نهایت، آخرین مرحله این پروژه، نمونه‌های اولیه توسعه‌یافته و سایر نمونه‌های آزمایشی را پایش و آزمایش نمود.

یافته‌ها نشان می‌دهد که فرآیند بهبودسازی نما که عملکرد انرژی مدارس، انتشار گازهای گلخانه‌ای، هزینه‌ها و ظاهر را بهبود می سازد، به قلمرو این حرفه نیاز دارد. اعضایی که در پروژه‌های مقاوم‌سازی ساختمان‌های مدارس ابتدایی دولتی مشارکت داشتند، عمدتاً باید تصمیمات اولیه طراحی نما را بر اساس ایده‌های حاصل از شناخت و استفاده از تجربه می‌گرفتند.

این پایان نامه و چارچوب مفهومی متعاقب آن، دید کلی جدیدی از مصالح ساختمانی مبتنی بر ضایعات و معرفی آنها به توسعه فناوری‌های نمای هوشمند را از طریق شاخص‌های علمی ارائه می‌کند که می‌تواند برای ساکنان، سازندگان، معماران و سیاست‌گذاران مفید باشد تا درک خوبی از پتانسیل نماهای هوشمند داشته باشند.

کلمات کلیدی: نماهای هوشمند؛ مدارس ابتدایی دولتی؛ بهبود سازی؛ استفاده مجدد از زباله؛ کارگاه؛ آسایش؛ پیشرفت تحصیلی؛ ارزیابی پایداری؛

Özet

Binaların inşası, bakımı ve işletilmesi günümüzde enerjinin neredeyse %40'ını tükettiğinden, mimarlar enerji tüketiminin azaltılmasında önemli bir rol oynamaktadır. **Bina cepheleri, yapıların ekonomik, çevresel ve sosyal performansları üzerinde önemli ve ölçülebilir bir etkiye sahip olabilir ve bu cephelerin güçlendirilmesi, günümüzün yaşlanan bina stoku sorununa kilit bir çözüm olarak görülmektedir.** Aşırı ısınma ve potansiyel iç ısı kaybı ile ilgili olarak, bina cephesinin şeffaf kısımları binanın enerji tüketimi üzerinde büyük bir etkiye sahiptir. Bu bağlamda, mimari kabuklarda akıllı sistemlerin kullanılması, enerji verimliliği, emisyonlar veya yapılı çevrelerdeki görsel temas derecesi ile ilgili umut verici çözümler olarak çağdaş talepleri karşılayabilir.

İspanya'da inşaat patlaması dönemleri, her dönemin tipik yapı tarzlarıyla birleşince, yapısal boşluk ve eskime riski altında olan büyük bir yaşlanan eğitim binası stoku ortaya çıkmıştır. Yalıtım eksikliği, yüksek hava sızması ve güneş kazancına rağmen, 1970-1980'lerden kalma bu tür yapıların çoğu bugün hala kullanılmaktadır. Dahası, Avrupa Komisyonu'na göre **İspanyol yapılarının yıllık %3'lük yenileme oranına göre, bugünkü binaların çoğu 2050 yılında hala kullanımda olacaktır**.

"Bu doktora tezinin temel amacı, bütünsel ve yenilikçi bir sürdürülebilirlik değerlendirme modeli aracılığıyla binalarının ekonomik, çevresel ve sosyal sürdürülebilirlik performanslarını optimize etmek için mevcut cephelere akıllı hizmetleri analiz etmek, geliştirmek ve teşvik etmektir".

Bunu yapmak için, bu tezin ilk aşamaları, sistematik incelemeler ve meta-analizler raporlama standardı için tercih edilen raporlama öğelerini izleyerek, kapsamlı akıllı cephe sistemleri, malzeme mühendisliğindeki gelişmeler, kullanıcı talepleri, otomasyonlar ve bunların küresel sürdürülebilirlik performansları hakkında 800'den fazla araştırma makalesinin derin bir dokümantal incelemesini gerçekleştirmiştir.

Ön araştırmalardan elde edilen sonuçlara dayanarak, aydınlatma ve termal konfor seviyelerini optimize ederek öğrencilerin akademik ilerlemesini hedefleyen İspanyol devlet okulları bağlamında farklı düşük maliyetli ve çevre dostu dinamik cepheler prototip haline getirilmiştir. Bu prototipler, okul öğrencileriyle yapılan katılımcı atölye çalışmaları sırasında belediye katı atık malzemeleri kullanılarak geliştirilmiştir. Bu konseptin, **atıkları yeniden kullanım döngüsüne geri döndürerek toplumumuzun kritik** atık üretiminin farkındalığını ve daha iyi yönetimini teşvik etmesi beklenmektedir.

Toplanan verilerden, akıllı cephe tasarımı ve uygulamasının karmaşık bir karar verme sürecinden geçtiği anlaşılmıştır. Yatırımın maliyeti ve uzun vadeli doğası, cephe kararının stratejik olduğu anlamına gelmektedir. Bu doğrultuda, bir sonraki aşamada, konuyla ilgili disiplinler arası uzmanların katılımıyla analiz, değerlendirme ve tasarım için derinlemesine keşif metodolojileri ve araçları yürütülerek akıllı cephe projelerinin uygulamadaki gerçekliği incelenmiştir. Son olarak, son aşamada geliştirilen prototipler ve çeşitli atık maddelerin diğer test örnekleri deneysel olarak izlenmiş ve test edilmiştir.

Bulgular, okul binasının işleyişini, enerji performansını, emisyonları, maliyetleri ve görünümü karşılayan cephe güçlendirme sürecinin meslek alanını gerektirdiğini göstermektedir. Kamuya ait ilkokul binalarının güçlendirme projelerinde yer alan üyeler, esas olarak bilişten kaynaklanan fikirlere dayalı olarak ve deneyimlerden yararlanarak ilk cephe tasarım kararlarını vermek zorunda kalmıştır.

Bu tez ve onu takip eden kavramsal çerçeve, akıllı cephelerin sağlayacağı potansiyel katkıların iyi anlaşılması için bina sakinleri, inşaatçılar, mimarlar ve politika yapıcılar için faydalı olabilecek bilimsel indeksler aracılığıyla atık bazlı inşaat malzemelerine ve bunların akıllı cephe teknolojilerinin geliştirilmesine girişine yeni bir genel bakış sunmaktadır.

Anahtar Kelimeler: Akıllı cepheler; Devlet ilkokulları; Güçlendirme; Atıkların yeniden kullanımı; Çalıştay; Konfor; Akademik ilerleme; Sürdürülebilirlik değerlendirmesi;

Chapter 1.
Introduction

1.1. Preamble

This Ph.D. research work consists in assessing intelligent façade strategies and solutions aimed at optimizing the sustainability of existing architecture by employing both experimental and simulation approaches. Part of the work regarded, in particular, three important aspects influencing the strategies and frameworks of the research thesis: (i) the economic, environmental, and social performance of the intelligent façade service; (ii) the condition of the defined case studies for the thesis which is the existing public educational architecture; and finally (iii) the main contributions which can be achieved through the application of intelligent façade in case studies.

Moreover, specific attention was given to the type of buildings that represents an important reality in the public school's construction panorama, due to their prevalence (over 80%), namely preschool and primary public-school buildings.

The innovative aspect of the work presented in the dissertation is mainly represented by the integration of new low-cost intelligent façade technologies and the application of multidisciplinary tools to evaluate the economic, environmental, and social features of the proposed solutions in different spatial areas of classrooms, and also their technical and mechanical behaviors.

Therefore, given the multidisciplinary nature of the performed study during the Ph.D. course and its outcomes, the four chapters of this dissertation are based on four published research articles. In these research articles, the undersigned Ph.D. candidate participated as the main author in three Q1 indexed journal articles, and as the co-author in one Q2 indexed journal article. These articles of reference during this Ph.D. research study are as follows:

> ***1. Article A: Sustainability Performance by Ten Representative Intelligent Façade Technologies: a Systematic Review,*** *S. Habibi, O. Pons Valladares, D. Peña, Journal of Sustainable Energy Technologies and Assessments, August 2022. https://doi.org/10.1016/j.seta.2022.102001*
>
> ***2. Article B: Sustainability Assessment of Household Waste Based Solar Control Devices for Workshops in Primary Schools,*** *O. Pons Valladares, S. Habibi, D. Peña, Journal of Sustainability, November 2018. https://doi.org/10.3390/su10114071*
>
> ***3. Article C: New sustainability assessment model for Intelligent Façade Layers when applied to refurbish school buildings skins,*** *S. Habibi, O. Pons Valladares, D. Peña. Journal of Sustainable Energy Technologies and Assessments, December 2020. https://doi.org/10.1016/j.seta.2020.100839*
>
> ***4. Article D: Evaluation of household waste materials for façade components in primary educational workshops: degradation behavior and mechanical properties of aged samples,*** *S. Habibi, O. Pons Valladares, T. Abt, Journal of building engineering, January 2021. https://doi.org/10.1016/j.jobe.2020.101573*

Apart from these articles, various scientific products have been generated which, despite not being part of this compendium, have also contributed to obtaining the knowledge presented in this document. Parts of these activities have been presented in the following three international scientific conferences:

> ***1. Conference paper 1: Towards more sustainable schools incorporating new solar control devices assembled during workshops of recycling waste materials,*** *O. Pons Valladares, S. Habibi, D. Peña, Oral presentation in 13th Conference on Advanced Building Skins, Bern, Switzerland, 2018.*
> ***2. Conference paper 2: Rehabilitation of educational architecture through waste-based intelligent façade layers,*** *S. Habibi, O. Pons Valladares, D. Peña, Oral presentation in International Congress on Water, Waste and Energy Management, Madrid, Spain, July 2018.*

*3. **Conference paper 3: Household waste potential for façades refurbishment: the case of Spanish schools solar control devices,** O. Pons Valladares, S. Habibi, D. Peña, Oral presentation in International Congress on Water, Waste and Energy Management, Madrid, Spain, July 2018.*

Furthermore, the Ph.D. candidate has also:

1. Codeveloped and published a utility model of waste-based solar control devices;
2. Reviewed several papers for international scientific journals;
3. Took part, as didactic support, in the teaching activities regarding the intelligent façades;
4. Participated in the UPC Recircula challenge 2021 and was selected as the top 10 groups.

These projects have been attached in Appendices A to G of this research thesis.

The following sections of this chapter outline the program and structure for this research thesis and introduce the contents of the following chapters. Then backgrounds of the research topic and problems are presented to orientate the reader toward this dissertation rationale. Thereafter, the goals and objectives are outlined to define what this research expects to achieve. Finally, this chapter presents the methodologies applied for performing this research study.

1.2. Structure of the dissertation

The structure of the thesis is organized into six chapters distributed among three main parts. The **1st Part**, which is **Chapter 1**, sets the framework, objectives, and methodologies. The following four chapters are the **2nd Part**, which contain the results included in this Ph.D. research. Each chapter in this part includes one of the aforementioned four published research articles. These chapters present the following information regarding each research article: (a) summary, (b) contribution to the thesis, (c) candidate's contribution, and (d) a copy of the published version. It is necessary to mention that the orders of the chapters in the **2nd Part** are based on each chapter's objectives and the chronological order of the articles has been neglected due to differences in their performing and publishing procedures.
Finally, the last part is a conclusive **6th Chapter** that highlights the main findings and presents possible future developments based on this research project. The following Figure 1 presents a flow chart that is a conceptual map for this dissertation, which can guide readers throughout the reading of this manuscript.

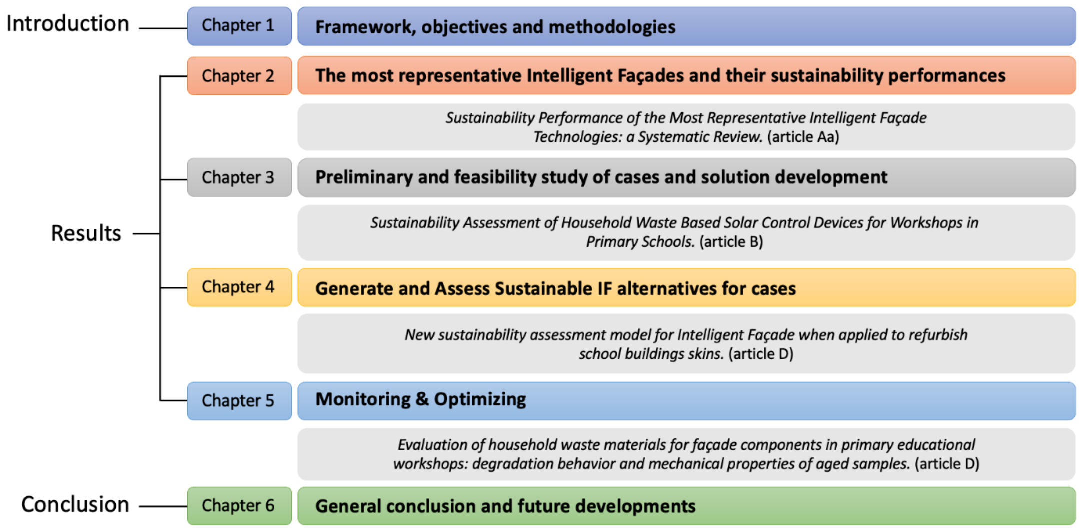

Figure 1. Conceptual map for this dissertation.

1.3. Motivation and justifications

This thesis investigates inclusive existing intelligent façade technologies and their potential in refurbishment projects which can contribute to improving the quality of existing edifices in all aspects. By incorporating these technologies, energy and comfort performance is expected to increase by (a) reducing heat transmission and (b) increasing solar heat, daylight, natural ventilation, and solar gains control.

During its primary investigation phases, this research thesis has found that there is a big gap in available literature about the technical performance of IFs and the long list of contributions that these technologies can provide. This gap causes an unclear framework on IF development and follows uncertainties between façade developers, decision-makers, or dwellers regarding these technologies.

Accordingly, to the best knowledge of the candidate, this research thesis studied and investigated IF technologies, their main developments during the last decade, and their contributions to both refurbishment and new projects. The **2nd Chapter** of this research thesis carried out this process by exploring and mapping the economic, environmental, and social performances of outstanding IFs, in the main scientific databases. This chapter has found that IFs can provide numerous sustainability contributions to existing architecture which generate negative environmental impacts such as high emissions, high energy consumption, and low comfort levels. Accordingly, promoting the application of intelligent services in façade refurbishment projects is one of the main motivations of this research thesis.

The **3rd Chapter** of this research thesis reviewed more than 100 reports on Spanish public schools' problems and the main challenges these schools face. This review found that a large percentage of Spanish school buildings have obsolete ventilation, thermal fittings, lighting, and acoustic solutions. This review found the lack of solar control devices as one of the main issues in Spanish public schools. This research thesis, for the first time, evaluated the satisfaction level of the teaching team regarding the classroom solar control devices in three primary schools through a questionnaire completed in the municipality of Barcelona. These analyses found out that these school architectural spaces, in their present state, were hindering those responsible for district budgets to operate these poor-performing buildings, and, in consequence, there were steady increases in utility costs.

Moreover, the review from the **2nd Chapter** found that the application of intelligent façades (IF; Table H1 in Appendix H presents a complete list of abbreviations) in public educational centers required a transition in economic aspects due to their high costs in fabrication, assembling, and maintenance phases. The **2nd Chapter** showed that the process to apply IF systems that fulfilled school buildings' sustainability performances in terms of energy, emissions, costs, comfort, and appearance, required multi-dimensional assessment models and multi-disciplinary professionals.

This research thesis contributed to increasing IF technologies' economic performances by introducing Municipal Solid Waste (MSW) materials in their development process. Accordingly, **Chapter 3** generated and assessed 96 different solutions of waste-based solar control devices for the case studies through a new multi-criteria decision-making (MCDM)-based assessment model combined with general morphology analysis (GMA) and focus group tools. All assessed solutions contribute to providing maximum lighting, thermal comfort level and energy efficiency for the studied cases. Being mainly composed of waste products, they have almost zero-cost and zero-emission factors. Three of the most sustainable solutions have been developed during eight workshop sessions with pupils in the three schools included in this study. These workshops were established by a group of education professionals and are compatible with children's safety. These workshops and pupils' incorporation in the development process of solar control devices have been established to promote educational programs on global waste problems and subsequently increasing society's knowledge which is important in the circular economy as has been recommended by many researchers.

In this context, **Chapter 4** studied whether IF technologies were sustainable solutions for the optimization of these school buildings or not. Thus, five outstanding recently developed IFs in high-cost edifices have been assessed using a novel Integrated Value Model for Sustainable Assessment (Modelo Integrado de Valor para una Evaluación Sostenible – MIVES) + Delphi model. This new model was, for the first time, developed and theoretically applied within a framework for IF implementation on refurbishing projects of existing educational architecture. This chapter, based on results of this application, proposed a new framework to develop new sustainable and low-cost IF technologies adapted to Spanish public primary schools.

Nevertheless, in order to seriously practice and promote household waste materials as a low-cost alternative for developing IFs, the professionals involved need to understand the properties of the replaced materials in depth. Accordingly, the **4th Chapter** of this research thesis carried out an experimental campaign on waste materials that rigorously tested numerous specimens to study their degradation behavior and their unreported mechanical properties. This chapter found out that waste materials composed of HPDE, PET, and Tetra Pak are approved to be used for the developed solutions.

1.4. Objectives

To this end, the main objectives of this doctoral dissertation are:

1. to move forward to a more consistent body of knowledge regarding IF technologies, their functions, their evolvements, and trends and their sustainability performance for researchers, façade developers and dwellers among other involved stakeholders;

2. to develop different novel and low-cost, environmentally and socially friendly façade systems that incorporate intelligent technologies geared to refurbish existing façades.

3. Develop a new sustainability assessment framework capable of scrutinizing problems, generating solutions alternatives, assessing solutions, prototyping and developing solutions based on reliable and updated data.

The following specific objectives support the prior general objectives:

1. to explore the state-of-the-art of IF practices in the built environment and their global sustainability performance in literature through deeply qualitative analysis.
2. to assess the sustainability performance of extensive IF technologies through a novel comprehensive sustainability assessment model.
3. to increase pupils' lighting, acoustic, and thermal comfort levels and the subsequent optimization in their academic performances.
4. to promote reusing waste material in the construction industry as a method to reduce final production costs through experimental campaigns on mechanical and fire properties of waste materials.
5. to increase pupils' knowledge regarding sustainability impacts in their living environment and global waste problems through teaching reusing strategies in workshop programs.

1.5. Methodology

In this research thesis, the process of sustainable refurbishment through IFs has been developed and carried out through a six-phases procedure based on previous sustainable refurbishment models. Figure 2 shows these phases, which are:
P1) Preliminary study: present a general input from each side of the research project's targets, limits, and scopes in terms of problems, challenges, approaches, solutions, and benefits.
P2) Feasibility study: present status of a context with refurbishment needs and building-level evaluations.

P3) Generate solutions: design various solution alternatives and strategies based on the context and building-level requirements and problems.
P4) Evaluation: justification and assessment of strategies and solutions and prepare for delivery.
P5) Development and implementation: securing required financing and procurement for construction.
P6) Monitoring & testing: finalize each aspect of the process, commissioning, and performance analysis.

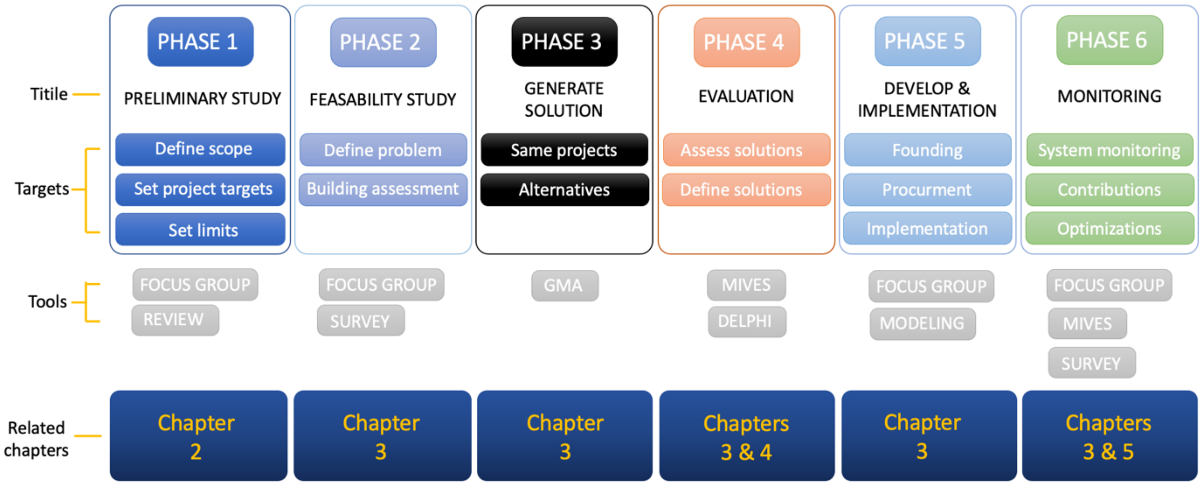

Figure 2. Carried out phases and applied methods in each phase and related chapters

In the 1st **Phase**, a precedent analysis was needed to set the objectives and limits of the study. The **1st Phase** set a comprehensive preliminary study to create a knowledge basis of IF technologies and their advancements in **Chapter 2**. This phase started to investigate frameworks related to outstanding IFs, considering global aspects during the whole life cycle from cradle to grave, including design, production, assembling, use, and end of life. In general, this preliminary phase includes interviews with various experts and stakeholders, a general study on the sustainability and technical performance of IFs, a general analysis of refurbishment strategies, and a collection of reference projects.

A feasibility study in the **2nd Phase** converts the defined boundaries in the **1st Phase** into the reasoning of the district and building levels. The feasibility study supports decision-making regarding: (a) time and resources available, (b) representative case studies, (c) potential professionals, and (d) business potential for users and owners. This decision-making process has incorporated interviews of focus groups, statistical data, and the collection of information through reviews and survey-based approaches. This phase defined a simplified set composed of three public primary schools located in three representative municipalities within the greater metropolitan Barcelona area. The technical conditions and performances of this set also have been collected through surveys by the teaching team. The adopted focus group method in this phase captured valuable information that will help to better manage the process of problem definitions. The essential steps in conducting a Focus group have been published in detail in the article presented in **Chapter 3** of this manuscript.

Phase 3 generates solution alternatives based on the previously identified problems in **Phase 2**. This third phase supports the solutions generation process via the GMA tool considering the requirements in this specific study. To do so, first, the main parameters and their value range have been defined; second, the study limited the relevant solution space by examining the internal relationships between parameters using CCA and a cross-impact matrix ensuring the consistency and coexistence of each possible pair. This analysis took into account logical contradictions, empirical constraints, and normative constraints [34]. GMA is a complex methodology that involves analyzing a wide range of organized samples of alternatives and it was chosen precisely in order to be able to take into account all feasible alternatives without missing any interesting options [15]. The essential steps in conducting GMA have been described in detail in the article presented in **Chapter 3**. Nevertheless, the decision process of a façade solution for the sustainable refurbishment of schools has been characterized by complexity – multi-disciplinary knowledge, multi-spatial and time scales –, uncertainty – many variables, inadequate information and data availability –, and urgency – the urgency of actions toward challenges like climate change.

Accordingly, **Phase 4** develops a new MCDM-based novel integrated sustainability assessment model during various sessions of seminars with professionals and applied it to define generated solutions for the case studies. An MCDM process can cover a single objective, or multi-objectives as targets to ensure that the defined solutions meet the refurbishment requirements [35]. In the MCDM methodology, the integration of LCC and LCA methodologies can select the most low-cost and environmentally-friendly refurbishment solutions for schools among all generated solutions in **Phase 3**. The social requirements can also be generated considering educational standards adapted for the specific case study. The definition of this new model followed the Integrated Value Model for Sustainable Assessment (Modelo Integrado de Valor para una Evaluación Sostenible – MIVES) [36] and Delphi [37]. MIVES is a customizable and agile sustainable assessment model that enables the overall assessment, comparison, and ranking of alternatives [21]. Simultaneously, the Delphi method, as an internationally recognized method, had been adopted to: (a) control and minimize possible bias, (b) elicit and refine a group of professionals, and (c) obtain required reliable data and judgment from an expert on a specific topic [38,39]. The incorporation of developed models defined the most sustainable façade refurbishment solutions for the case studies. **Chapter 3** and **Chapter 4** explain in detail the whole protocols of MIVES and Delphi and all the subsequent steps to define sustainable façade solutions.

Phase 5 models and develops three of the defined solutions in three defined primary schools during participatory workshops with pupils. A utility model in Spain has been successfully developed regarding the system to design and produce these prototypes. These three applications' development process started with approval by the building's administrators – the Catalan Department of Education and the three schools – and with its funding. These prototypes and their workshops have been developed within the framework of the participation in the national project funded by FBBVA, the project "New solar control devices for sustainable school architecture workshops". This phase also made a cost estimate for the project and ensured that the funding covers both design and construction requirements. In this phase, district educational organizations through the focus group method, participated in developing workshops and approving the project and its progress. **Chapter 3** presents the process of prototype development by pupils and details of each prototype.

The final phase of this research thesis resulted in the presented refurbishment process by monitoring, testing, and exploring contributions. **Phase 6** analyses the performance of the developed systems across various sustainability aspects such as energy, ventilation, and lighting performance. It does so by assessing data from both modelling and real-time data collection considering various occupancy hours. This phase developed surveys to analyze: (a) the outcomes of workshops on pupils' increased knowledge and (b) the outcomes of developed solutions on their comfort levels and academic performances. This phase also applied the focus group tool in developing surveys [40]. Moreover, this phase analyzed the properties of the introduced solutions in depth through experimental campaigns that rigorously tested the degradation behavior and the mechanical properties following ISO 4892-1:2016 and ISO 4892-2:2013. **Chapters 3** and **5** collect the results of this phase and its experimental campaigns and surveys, which motivated collaborators to join the project and increased expectations and documents for further developments.

Chapter 2.
The most representative Intelligent Façades and their sustainability performances

As previously said in Section 1.5, this chapter covers this thesis **Phase 1** and presents the thesis results published in **Article A** "*Sustainability Performance of the Most Representative Intelligent Façade Technologies: a Systematic Review*". A copy of this article is attached at the end of this chapter. This chapter develops a knowledge based on the current state-of-the-art and advancements on the economic, environmental, and social performances by IFs, from the main scientific databases.

2.1. Introduction

The emerging climate and economic crisis are driving rapid and substantial regulations within the construction industry. These regulations are expanding toward more extensive use of sustainability criteria to mitigate this crisis negative consequences. Sustainable development requires the consideration of a whole host of interconnected elements, such as the reduction of energy demand and water consumption, minimizing waste and pollution, and providing efficient comfort [41,42]. The construction sector is responsible for around half of energy consumption, greenhouse gas (GHG) emissions, and depletion of natural resources worldwide [43] and has a important room for improvement. The sustainable construction approach has priority objectives such as closing the materials and water cycles [44], reducing energy demands, and also 'greening' the energy supplies [45].

Given this context, IFs can offer considering flexibility in design and, therefore, introduce significant benefits regarding environmentally friendly functions at both building and urban scales [46]. IF systems have become a key option to achieve sustainable development goals in the construction sector. IFs incorporate variable technology, which can adapt itself to provide comfortable conditions inside the building whatever the lateral environmental and economic conditions, might be, in any particular building location [47]. Other direct and indirect benefits of these smart infrastructures include noise reduction [48], improved air quality [49], aesthetics [50], the value of a building [51], credits in the green building rating system, etc. Integrating intelligence into modern façades can also have a psychological benefit for human health [52].

A step from contributions that IF provides, a decision for the application of these technologies, seems to have always been among the main challenges [53,54]. The decision to adopt these technologies ranges from economic reasons to more technical ones. The "intelligence" of façades is usually linked to drawbacks such as higher initial investment, and operational and maintenance costs. Moreover, IF available technologies are variable along the time and the region. This fact brings complexity to the quantification of IF's behavior, and consequently, it may compromise IF's implementation in buildings considering that engineers and architects need to control all the design variables, especially during the design phase [55].

Considering the evolutionary path that sustainability is undergoing, a deeper knowledge of these practices in the IF sector is essential to identify which practices are currently being performed and which still need to be implemented or improved. Research on IFs had been conducted in great detail from a variety of perspectives, such as shading elements [56,57], airflow analysis [58,59], ventilation [60,61], lighting [62–64], and sequestrated emissions [65]. However, there is a lack of clarification and guidance on how IF technologies can leverage sustainable building development and cleaner production in the supply chains. Accordingly, exploring the state-of-the-art in the IF topic will serve as a driving force in identifying academic gaps to support new value creation opportunities, facilitating stakeholder decision-making and greater integration between them.

To do so, this chapter, for the first time, conducted a Systematic Literature Review (SLR) and Prisma [66] of global sustainability performance related to 10 IF alternatives based on deeply qualitative analysis, which is still missing in the literature. SLR is a transparent, reliable, and replicable method to consolidate research findings in a specific area and identify research gaps that can guide future research [67]. The 10 studied IF alternatives are: 1) Vertical Greenery System (VGS); 2) Double Skin Façade (DSF); 3) Ethylene tetrafluoroethylene (ETFE) cushion; 4) wind wall; 5) Photo Bioreactors (PBR); 6) Building-Integrated Photovoltaics (BIPV); 7) Building Integrated Solar Thermal (BIST); 8) Titanium Dioxide nanotechnology (TiO_2); 9) Auto-blinds; and 10) Electro-active façade technologies. A complete description of these façades and their details have been depicted in Appendix C in Section 2.4. These alternatives are the most representative façade technologies which were applied and investigated and examined during the last decade in different regions and climates. This study identified and reviewed more than 800 articles around the mentioned technologies using the SLR method from 2010 to 2020.

The results of this review have been extracted and expressed according to the 16 sustainability indicators for IF technologies assessments defined in this thesis, which are explained in depth in **Chapter 4**. Moreover, the results have been normalized and divided into a thematic analysis including applied methods, contents, publication year, and descriptive analysis of their sustainability performances. The thematic results illustrate that energy saving, flexibility, and energy efficiency are the most studied indicators; while the most applied assessing methodologies were experimental and/or numerical methods. On the other hand, the descriptive results indicate that IF technologies mainly have lower performances in terms of economic and environmental dimensions of sustainability, while in terms of social sustainability their performance is considered satisfactory.

Nevertheless, from perspectives of new IF research directions, this review suggests further explorations of cost-effective, recyclable, reusable, and flexible technologies. These new works should also move forward to real applications.

2.2. Contribution to this thesis

The first key contribution of **Article A** to this thesis is to undertake an SLR of the available literature in the field of outstanding IFs and their specific sustainability values in all aspects, which provides a useful foundation for the next chapters of this research thesis to rely on. This chapter presents specific values in terms of cost, energy, comfort, and all other indicators for the previously presented ten IF alternatives.

The second key contribution of this article is to provide a sufficient body of knowledge regarding the potential capabilities of IF technologies compared to more common façades. This chapter contributes to increase the scientific knowledge of IF technologies for architecture. This review and its subsequent conceptual framework provided a descriptive overview of 10 extensive IF technologies and their different functions, through scientific indexes that were useful for the candidate to have a good understanding of IFs.

Another contribution of this article is to analyze what has already been done in terms of sustainability practices in the IF sector for architecture. This analysis opens avenues to distinguish economic, environmental, and social indicators and related evaluation and experimental tools and methods.

These contributions show that there is great variability and no standardization yet in the selection of indicators to assess the sustainability of IF façades, especially in economic and social analyses. Moreover, this SLR highlights the main conceptual frameworks and approaches for the evaluation of indicators to achieve buildings' sustainability across different contexts. For instance, to evaluate the thermal performance of an IF alternative, one of the overall objectives of this research paper is to investigate real-scale experimental calculations and approve the best approaches. Moreover, key parameters such as the spatial configuration of the IF, the width, the orientation, and the climatic zone have been reviewed and used as clustering criteria. This SLR selected the best strategies and tools to understand how sustainability assessment methods are incorporated into the design process of a façade, and where improvements are needed. Accordingly, regarding the sustainability assessment indicators, this SLR concludes that:

a) The economic indicators should cover all LCC impacts and phases, including design, development, transportation, installation, operation, maintenance, and end-of-life.
b) The environmental indicators should include all LCA impacts during all design, development, transportation, installation, operation, maintenance, and end-of-life phases.
c) The social indicators should include a) construction added values as labor safety and price increment, and b) user-added values as and user safety, lighting and thermal and acoustic comforts.

Moreover, the results of the thematic analysis in this systematic research provide important information about current and future research directions. This analysis guides the thesis author to identify which IF alternatives and sustainability sectors there are gaps to explore. In general, the framework and future research directions proposed in this study should support a paradigm shift towards sustainable IFs and, will contribute to the implementation of IF systems for enhancing sustainability in the construction sector as a whole.

2.3. Contribution from the candidate

This SLR research article has been carried out over two years of investigations and examinations by the thesis author, who is the main author of this review. In this SLR, the candidate defined the methodology, software, formal analysis, investigation, resources, data curation, writing of original draft, and calculation. The other article's authors are the thesis co-directors, who mainly supervised and provided advice to the main author.

The applied SLR methodology in this article has 4 phases to which the candidate has contributed as follows:

a) Preparation: generating 160 search codes for identification of scientific works in databases.
b) Identification: identifying an extended list of 1230 scientific literature from November 2019 to May 2020. After carefully retrieving, examining, and screening these documents, 815 fit this review's purposes.
c) Classification: classifying the identified literature based on IF type, sustainability-related contents, publication year, and applied methodologies.
d) Analysis: examining in detail each dimension of sustainability in the revised literature. The results of these analyses have been classified into: (i) specific values of each indicator, (ii) comments that clarify the function of each IF system, (iii) criticisms that indicate the defects of an IF in a disapproving way, and (iv) praises that express the approval for an IF system.

The candidate chose the SLR method, which seeks to systematically draw together all known knowledge on a topic area and is known as one of the best types of literature review methodologies. In addition, these methodology applications demonstrated their capability to bring robustness and specifically filter the information.

Finally, the candidate was in charge of the article publication process in the Sustainable Energy Technologies Assessment journal. This process included the review's submission, revision, and answers to the editor and reviewers, which the thesis author led.

2.4. Article A

This section presents the published Article A. As mentioned, this article covers the first phase of this research thesis and includes the steps followed in this phase and the thematic and descriptive results of the SLR on the sustainability performances of 10 IF technologies.

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Review article

Sustainability performance by ten representative intelligent Façade technologies: A systematic review

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ABSTRACT

Recently, intelligent façades (IFs) have become key factors to achieve sustainable development goals in the architectural sector. Research in this area is steadily growing. However, there is lack of conclusive results in available literature about IF's sustainability performance. Thus, this article aims to identify and map the economic, environmental, and social performances by IFs, in the main scientific databases through a systematic review following the preferred reporting items for systematic reviews and meta-Analyses reporting standard. This methodology has identified main search codes and more than 800 articles submitted from 2010 to 2020. The results from the literature regarding ten types of IF technologies are extracted, classified, normalized, and expressed according to previously developed 16 sustainability indicators. Results indicate that, in terms of economic and environmental dimensions, IF technologies mainly have lower performances while their performance in terms of social requirements is considerably satisfactory. This review and its subsequent conceptual framework provide an overview for IF introduction, through scientific indexes that can be useful for occupants, builders, architects, and policymakers to have a good understanding about the potential contributions IFs provide. Nevertheless, in perspectives for new IF research directions, this review suggests further explorations on cost-effective, recyclable, reusable, and flexible technologies.

Introduction

In response to present global sustainability problems, new economic, environmental, and social goals and measurements are being approved worldwide in many areas [1]. In the construction sector, environmental impacts account for 25 to 40 percent of the world's total carbon emissions and around 36 percent of global energy consumption [2,3]. To reduce these figures, intelligent buildings are an interesting solution consisting of edifices capable to adapt themselves to their environment by means of perception, reasoning, and action systems that are capable to conduct energy, material, and information exchanges. This adaptiveness enables buildings to function separately as a protective or regulatory controller in terms of light, heat, sound, ventilation, and air quality. These solutions involve the introduction of information technology into design principles, promoting the potential use of green energy supplies, minimizing energy demand, maximizing comfort, and other aspects [4].

Wigginton and Harris [5] name these compositions of construction elements confined to the outer, weather-protecting zone of buildings as intelligent façades (IF; Table H1 in Appendix H presents a complete list of abbreviations). IFs perform individually or cumulatively to respond predictably to environmental fluctuations, to maintain comfort with the least use of energy, considering factors such as building operation, maintenance, upgrading, tuning and life cycle. By adopting these IF technologies, buildings' energy performance improves by optimizing: a) insulation, b) daylight usage, c) ventilation, and e) solar gains [5-7]. There are also new IF technologies engineered to generate energy, reduce bills, purify the air, generate breezes, and contribute to human well-being [8-10].

From recent investigations, about 70–80% of energy consumption [11] and 20–30% of greenhouse emissions [12] can be prevented by IF service contributions. However, simultaneously, in complex façades, mechanical and electrical systems might cause construction cost increases of up to 40% [13]. These cost augmentations could worsen with the addition of lifetime costs from involved systems, including maintenance, replacement and operational energy expenses [5]. Therefore,

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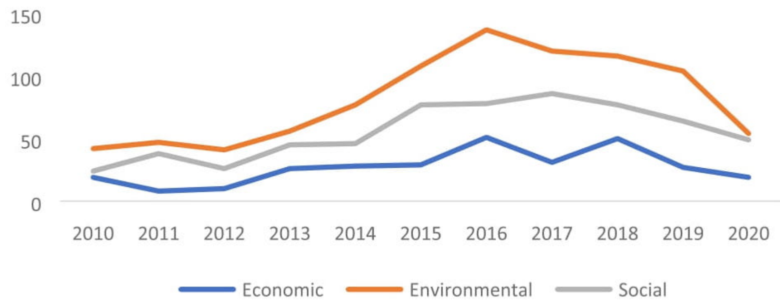


Fig. 1. Trending process of IF sustainability publications from 2010 to 2020.

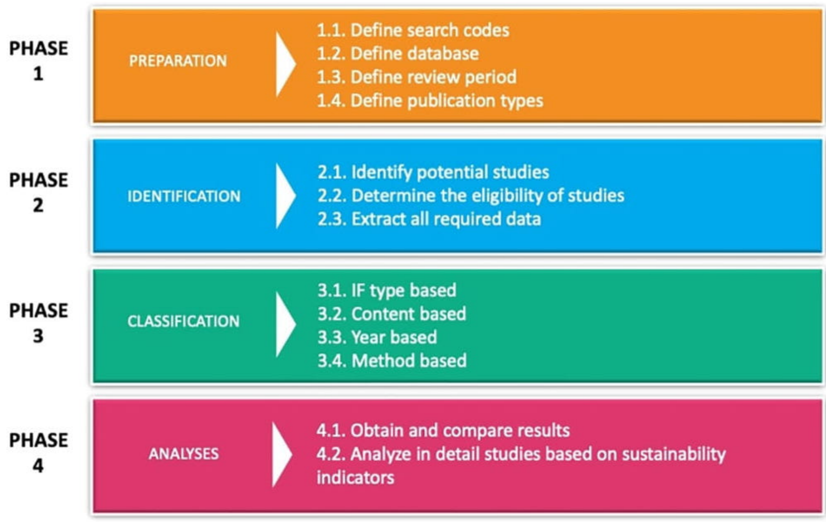


Fig. 2. Main phases and steps followed in this review article.

Table 1
Qualified types of intelligent façades and their relevant technologies and specifications.

IF type	Example	Location	Pos	Res	RS	Parameters	Score
VGS	Geotextile felt	Madrid	Ex	F	–	Mgl, Pfa, Chu, I, Roh, Asd, Sem, Aem, Pae, Ipv	12
DSF	The Gherkin	London	Ex	F	–	Mgl, Pfa, Chu, Cai, Crd, I, Coh, Roh, Asd, Sem, Ipv	13
ETFE	Media-TIC	Barcelona	Ex	A	–	Mdl, Mgl, Crd, I, Coh, Roh, Asd, Sem, Ipv	12
Wind-wall	SFPUC	San Francisco	Ex	A	WG,PE	Mgl, Cai, Crd, Egn, Sem, Pae, Ipv	10
PBR	BIQ house	Hamburg	Ex	Hy	HP, BM	Mdl, Mgl, V, Cai, Crd, I, Roh, Egn, Asd, Sem, Aem, Pae, Ipv	19
BIPV	Solar office Doxford	Sunderland	Ex	A	PV	Mgl, Crd, I, Roh, Egn, Sem, Ipv	10
BIST	Bombardier' Canadair facility	Montreal	Ex	A	HP, PV	Mgl, Crd, I, Coh, Roh, Egn, Asd, Sem, Ipv	13
TiO_2 façade	Hospital Manuel Gea	Mexico	Ex	F	–	Mdl, Mgl, Pfa, Cai, Roh, Aem, Pae, Ipv, Psf	12
Auto-blinds	Al-Bahar	Abu-Dhabi	Ex	A	–	Mdl, Mgl, V, Cai, Crd, I, Roh, Asd, Sem, Pae, Ipv	13
Electro active	U.S. Bank Tower	Los Angeles	In	Hy	–	Mdl, Mgl, V, Crd, Roh, Sem, Pae, Ipv	10

Legend: vertical green system (VGS); double skin façade (DSF); ethylene tetrafluoroethylene cushion (ETFE); photo bio-reactor (PBR); building integrated photo voltaic (BIPV); building integrated solar thermal system (BIST); position (Pos); responsiveness (Res); renewable system (RS); references (Ref); external (Ex); internal (In); fixed (F); hybrid (Hy); automatic (A); wind generator (WG); piezoelectric (PE); hydro-power (HP); biomass (BM); photovoltaic (PV); maximizing daylight (Mdl); minimizing glare (Mgl); providing view (V); provide fresh air (Pfa); control humidity (Chu); circulating air (Cai); control radiation (Crd); insulation (I); collection of heat (Coh); rejection of heat (Roh); energy generation (Egn); attenuation of sounds (Asd); sequestrating emissions (Sem); absorbing emissions (Aem); provide aesthetic (Pae); provide safety (Psf); increase property value (Ipv).

optimizing building performance and its sustainability by using intelligent façades is a challenging process due to the multidimensional factors that need to be considered, such as emissions, cost, comfort and energy.

Accordingly, a rigorous literature review about IF technologies should be an interdisciplinary study on the aforementioned factors and could contribute to their global sustainability potentials. Thus, this review is based on a multicriteria decision-making process developed in a previous research study for ten specific IF case studies [14], in order to cover all factors and potential contributions. For the first time, this review explores the sustainability of these ten significant IFs in the built

Table 2
Sustainability indicators, most representative IF cases and generated search codes.

Sustainability indicators	Most representative IF	Search codes
I1- Fabrication and assembling cost	IF1- VGS	I1 + IF1 = SC1- Fabrication cost of VGS
I2- Annual maintenance cost	IF2- DSF	I1 + IF2 = SC2- Fabrication cost of DSF
I3- Annual operation cost	IF3- ETFE	.
I4- Dismantling cost	IF4- Wind Wall	.
I5- EE	IF5- PBR	.
I6- EC	IF6- BIPV	I10 + IF5 = SC105- Recyclability of bioreactor
I7- Annual Energy saving	IF7- BIST	
I8- Energy conversion efficiency	IF8- TiO_2 façade	.
I9- Annual Sequestered emission	IF9- Auto-blinds	.
I10- Recyclability	IF10- Electro-active	.
I11- Reusability		.
I12- Fabrication and assembling ease		.
I13- Flexibility		I16 + IF9 = SC159- Safety of auto-blinds
I14- Ventilation performance		I16 + IF10 = SC160- Safety of Electro-active
I15- Light performance		
I16- Safety		
16 Indicators	10 IFs	160 SC

environment and studies how different factors affect these IFs performance. This exploration of the research state-of-the-art in the IF sector will serve as a driving force in identifying academic gaps to support new value creation opportunities, facilitating stakeholder decision-making and greater integration between these stakeholders.

This present article has found limited documents that have reviewed the sustainability performance by intelligent façade technologies. Moreover, these former studies have reviewed IFs considering their partial sustainability performances, for instance carrying out LCA or LCC reviews. These include studies done by: (i) Talaei et al. [15] who reviewed the energy, light, and pollution performance of nine innovative building envelope technologies that interacted with solar energy; (ii) Böke et al. [16] who studied the existing definitions and key terms of intelligent façades; (iii) Meir et al. [17] who reviewed and summarized the literature on post-occupancy evaluation of different IF technologies. Nevertheless, the scope of IF-related systematic literature reviews (SLRs) has proliferated in recent years. A brief analysis of the last decade IF SLRs shows that from 2015 to 2018, sustainability is progressively considered, as presented in Fig. 1. However, to the authors' best knowledge, a broad and comprehensive sustainability SLR related to IFs across multiple disciplines has not been reported yet.

This present review also found that, during the last decade, many researchers have reviewed the sustainability of specific IF systems, and these reviews have focused on general studies and comparative analyses. For example, vertical green systems (VGS) have been investigated from various points of view such as VGS structures [18], plant species [19], or maintenance [20]. Building-integrated photovoltaic (BIPV) and building integrated solar thermal (BIST) systems have been also investigated considering their transparency [21], efficiency [22], or their economic aspects [23].

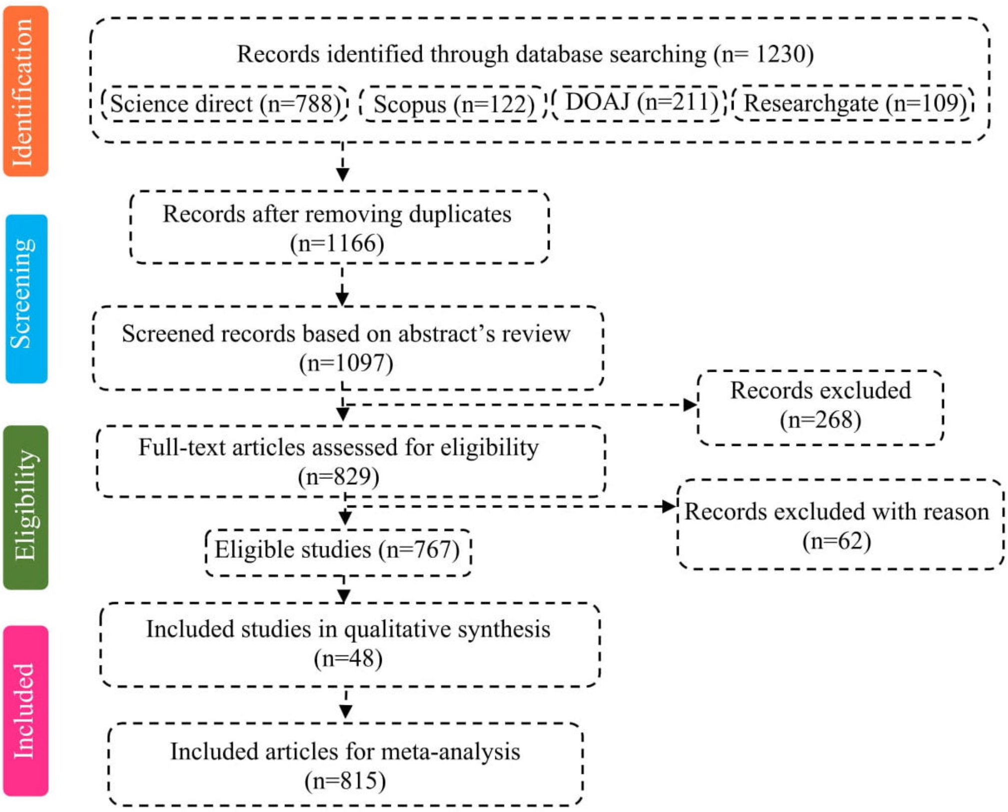


Fig. 3. PRISMA flowchart of search results.

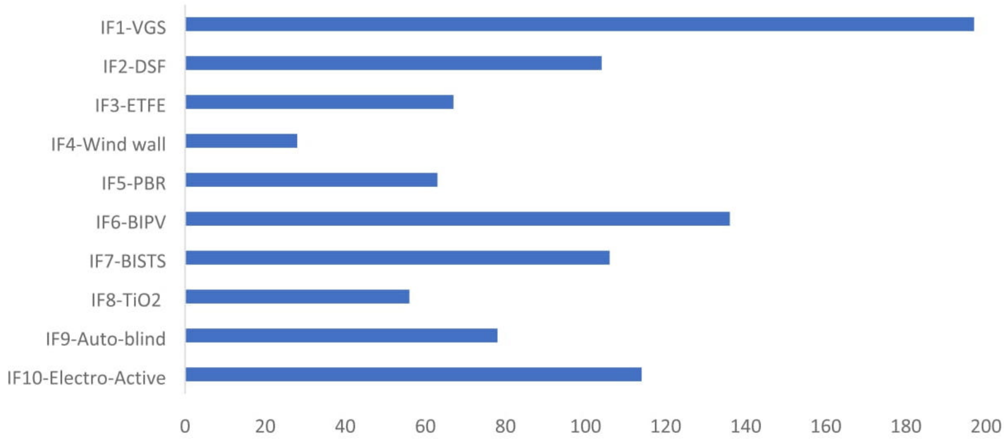


Fig. 4. Number of publications of each IF type from 2010 to 2020. Legend: vertical green system (VGS); double skin façade (DSF); ethylene tetrafluoroethylene cushion (ETFE); photo bio-reactor (PBR); building integrated photo voltaic (BIPV); building integrated solar thermal (BIST); titanium dioxide (TiO_2).

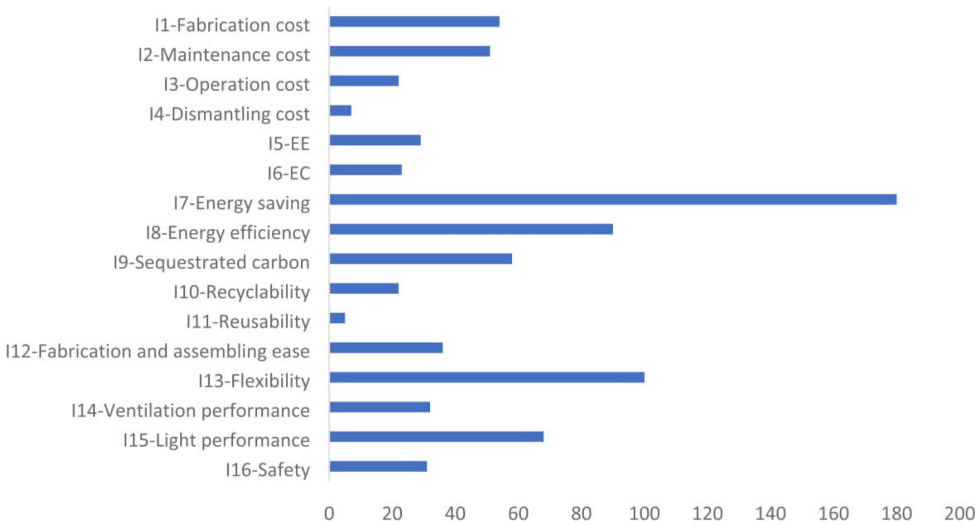


Fig. 5. Number of publications for each sustainability indicator from 2010 to 2020.

In this context, for the first time as previously said, this present study aims to provide a global sustainability SLR for developed IF technologies and interrelated fields of technical literature. Correspondingly, the four research questions proposed and addressed in this study are: "1. What are the main sustainability contributions by existing IF typologies?", "2. What is the research progress of sustainability topics within the IF field?", "3. What are the research gaps in the studied field?", and "4. What future research directions could address the present research gaps?".

To achieve this aim and address these research questions, a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was adopted. This review's findings expect to contribute to the development of a conceptual framework for IF technologies to achieve buildings' sustainability. To this end, the main contributions of the present study are: (i) to provide sufficient body of knowledge regarding potential capabilities for IF technologies compared to more common façades; (ii) to identify IF publications evolvements during the last decade considering each dimension of sustainability; and (iii) to identify and evaluate the main sustainability indicators in related literature about outstanding IF technologies; and (iv) to identify the main gaps to be investigated in the future.

After this **introduction**, Section 2 describes the research **methodology and steps followed**. Section 3 presents thematic and descriptive **results** and **discussion**. Section 4 summarizes **future research directions** while Section 5 draws **conclusions.**

Methodology

This present study has applied PRISMA because this reviewing method enables researchers to systematically search, appraise, and synthesize the research evidence linked to the analyzed topic [24,25]. The authors considered previously conducted research studies [26-29] concluding that PRISMA seeks to systematically draw together all

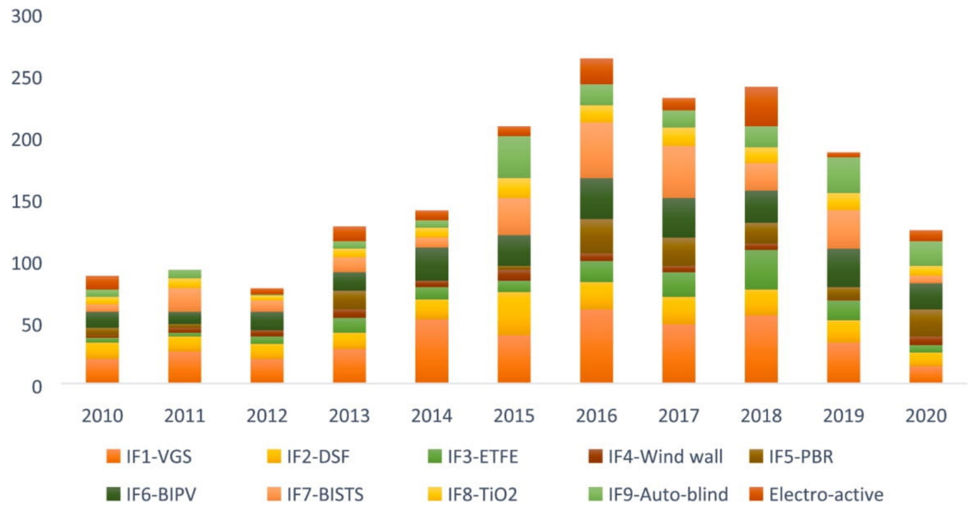


Fig. 6. Trending process of IF types from 2010 to 2020.

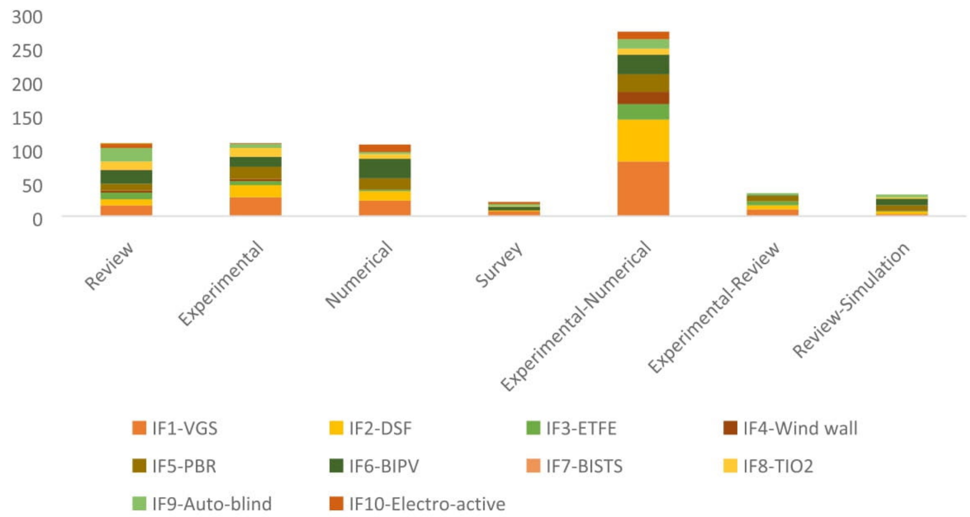


Fig. 7. Different applied methodologies in IF studies from 2010 to 2020.

known knowledge on a topic area. In addition, the application systematic literature review has demonstrated its capability to bring robustness and specifically filter the information [30]. Fig. 2 presents the four-phase research process used in this study, which strictly follows these review method protocols.

To carry out a broader and comprehensive review, step 1.1 defines the search codes this study employs. These codes result from linking the selected sustainability indicators with the most representative IFs. The selection of indicators is based on the aforementioned authors' newly developed sustainability assessment model, which assessed the sustainability of intelligent façade layers [14]. On the other hand, the list of representative IF technologies followed a specific protocol, presented in Table A1 in Appendix A. This protocol has been generated based on the studies around IF classifications and analyses [31-35], which the chosen IFs have scored at least 10 points in this protocol. Step 1.2 identifies the scientific works in the following databases: ScienceDirect [36], Scopus [37], Publons [38], DOAJ [39], and ResearchGate [40] respectively. Step 1.3 focuses the review on literature from 2010 to 2020 that Sustainable Energy Action Plans had legislated in many countries from Europe or Asia intending to reduce CO_2 emissions and energy demand [41]. Step 1.4 produces a specific protocol for the qualified types of the collected literature which included books, theses, journal articles, conference papers, and reports. The authors have defined these review parameters according to the previously mentioned research objectives.

The second phase identifies the potential studies obtained from the searches carried out. The applied PRISMA technique considered research and publications in parallel within the scopes and orientation of this study. During this identification process, some terms were added

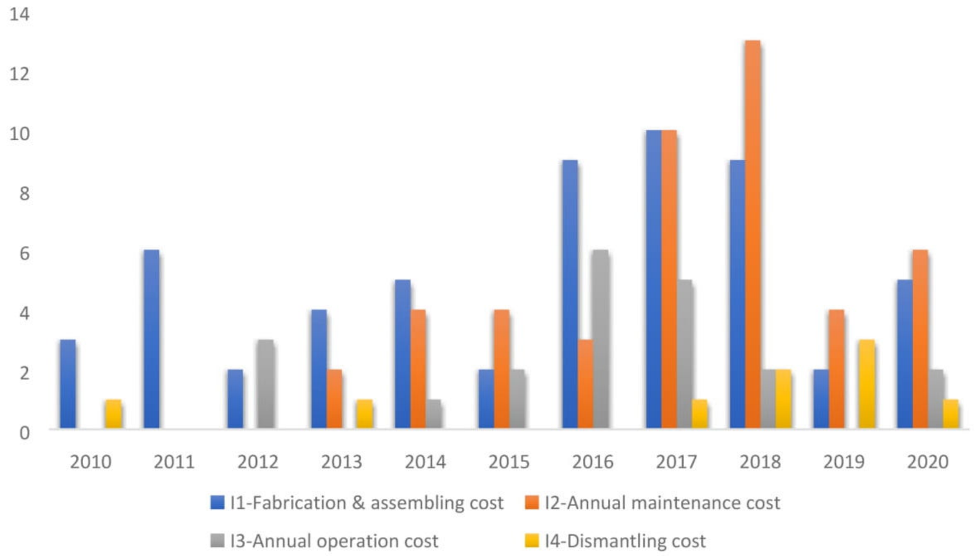


Fig. 8. Distribution of studies based on four economic indicators from 2010 to 2020.

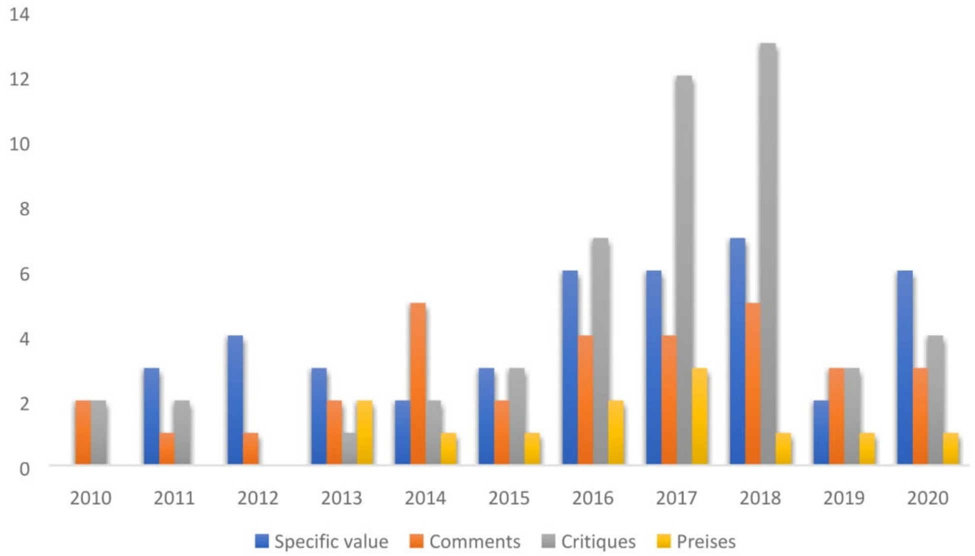


Fig. 9. Distribution of economic related studies based on their contents from 2010 to 2020.

as search codes when referring to the different types of IFs. There are three major steps for conducting the PRISMA method. Once step 2.1 searched in the current literature, step 2.2 determined the eligibility of articles, so a smaller number of eligible studies for this review remained [42]. Finally, step 2.3 extracts all required data in selected studies.

The third phase classifies the potential literature based on: (3.1) IF type, (3.2) sustainability-related contents, (3.3) publication year, and (3.4) applied methodologies. Its first step classifies literature based on the multiple or specific IF types that each publication investigates. Step 3.2 classifies the different sustainability indicators on which each publication focuses. Step 3.3 classifies the publication years of potential literature from 2010 to 2020. Finally, step 3.4 classifies the studied literature according to the applied methodology on each document.

The final fourth phase analyzes this classified literature based on the previously established sustainability indicators (see step 1.1). In this phase, during each year, each dimension of sustainability was individually examined in detail in the reviewed literature. This analysis classified its outputs on values, commentaries, critiques, and praises. These outputs are: (i) specific values on each indicator, (ii) comments that clarify the function of the system, (iii) critiques that indicate the faults of an IF in a disapproving way, and (iv) praises that express the approval for an IF system. Thus, this examination enables analysts to identify and classify the main strengths and gaps in outstanding IF cases, as well as their related sustainability performances.

Results and discussion

This section presents the results achieved by applying the

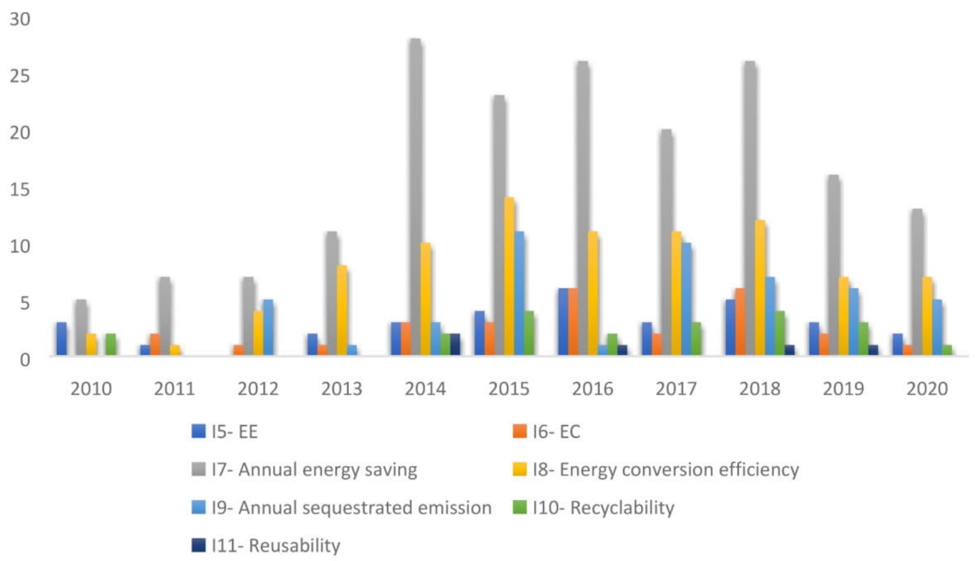


Fig. 10. Distribution of studies focusing on the analyzed environmental indicators from 2010 to 2020.

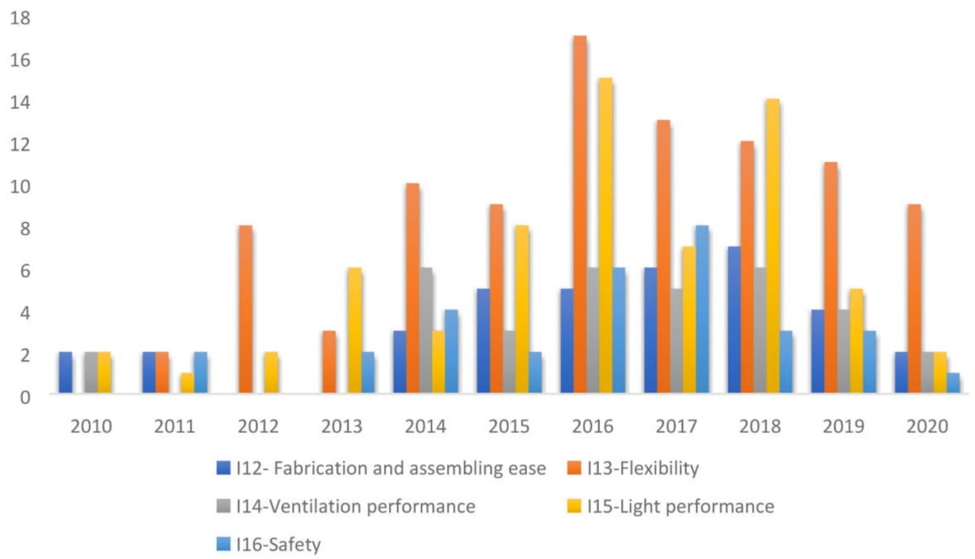


Fig. 11. Distribution of studies based on the five analyzed indicators from 2010 to 2020.

methodology presented in Fig. 2 to IF technologies. The following subsections present this process in four phases and 13 steps.

Phase 1. Preparation

As previously mentioned, the list of search codes results from linking both selected sustainability indicators and IF technologies.

The defined 16 indicators are: *I1) fabrication and assembling cost, I2) annual maintenance cost, I3) annual operation cost, I4) dismantling cost, I5) embodied energy (EE), I6) embodied carbon (EC), I7) annual energy saving, I8) energy conversion efficiency, I9) annual sequestered emission, I10) recyclability, I11) reusability, I12) fabrication and assembling ease, I13) flexibility, I14) ventilation performance, I15) light performance* and *I16) safety*. These indicators are the core of the previously developed innovative MCDM model to assess the sustainability of five intelligent façades for Spanish public primary schools. The process of defining indicators was done after several rounds of integrated surveys with professionals and achieving consensus among them, based on Delphi method protocols. This method enables the inclusion of the most qualified professionals among different fields of knowledge, in that case these professionals were: construction professionals, environmental specialists, façade developers, pedagogues, school administrators, and waste managers. Accordingly, this method, with its many features, determined the main sustainability indicators for the case study. Those indicators in that model focused on low-cost IF for school buildings, although those indicators could be adapted to other particular contexts after specific adjustments of boundaries, weights and value functions [14]. See Table B1 in Appendix B for a detailed list of these indicators,

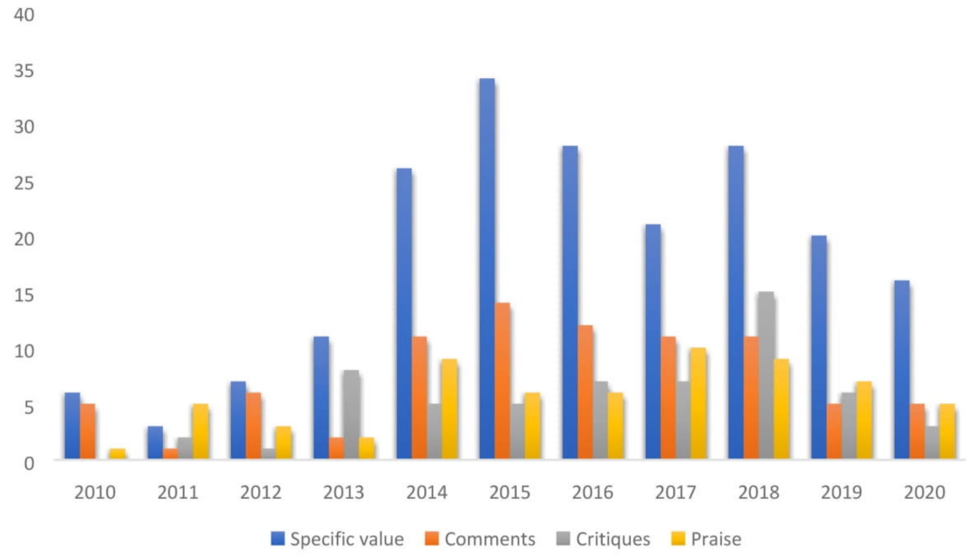


Fig. 12. Distribution of social related studies based on their contents from 2010 to 2020.

Table 3
Future research directions regarding the identified main gaps.

Sustainability branch	Future research directions regarding the identified main gaps
Economic	1. Provide IF dismantling strategies and investigate reuse materials acceptance;
	2. Clarify contributions from producers, suppliers and researchers and all other involving members in the total fabrication cost of IF products;
	3. Comprehensive economic analyses of wind harvesting technologies;
	4. Define the main economic potentials of inflating ETFE cushion façade;
	5. 5. Investigate algae harvesting equipment and their high-cost challenges;
Environmental	6. Review strategies to extend the energy efficiency of IF systems;
	7. Explore the high amount of waste produced by some IF technologies, their reusing potential, and their increased life time;
	8. Explore environmental contributions of TiO_2 nano particles and recommending worldwide extension;
	9. Carry out LCA analysis of different mechanical equipment in IF technology, focusing on their material flow analysis, material passports, EE and EC that rarely exist;
Social	10. Explore injuries and harm possibilities in IF development processes which may risk the health of laborers;
	11. Post-occupancy analyses considering stakeholders' and users' satisfaction on the built environment;
	12. Study labor working hours and required professionals for each alternative while considering other construction elements.

which generate 16 search codes that define the boundaries and structure rigorously in this review.

On the other hand, Table 1 shows the list of 10 qualified IF types along with a real example, which are definitely distinctive in terms of their functions, technologies used, operation patterns, and systems. Detailed sections for these IF alternatives have been depicted in Fig. C1 in Appendix C.

As depicted in Table A1 in Appendix A, all qualified IFs meet the minimum required score. These IF type examples are all large-scale building façades, from which nine of them have been implemented in an external façade part, to directly protect external environmental parameters such as wind, solar radiation, humidity, and temperature. However, both external and internal applications require numerous sensors to measure both exterior and interior environmental influences and transmit the obtained readings to a control unit [43]. Three alternatives are fixed. Five alternatives interact autonomously regarding environmental stimuli while users are not able to control the systems. The other two alternatives have hybrid movement systems that operate automatically while enabling manual personalization by users. Four IF cases integrate renewable energy systems that can provide energy for their own operation or for the building where the IF is implemented. These four IF types include current feasible renewable energy systems. As seen in Table 1, the control of natural light has been recognized as the main function in each IF to reduce artificial lighting, building energy consumption, and increase comfort. The other involved general parameters are to increase energy, thermal, environmental, and/or acoustical performances.

After selecting these 16 indicators and 10 IF alternatives, Table 2 displays the linking procedure to obtain the resulting search codes from this phase. Table 2 also gives five examples from the generated 160 search codes depicted in Table D1 in Appendix D.

Phase 2. Identification

Searches carried out from November 2019 to May 2020 resulted in 1230 studies matching the initial search codes. Based on PRISMA technique checklists, the review excluded: duplicated articles, non-English language written publications, letters, magazines, short notes and blog posts; which left 1166 publications. Then, after examining the title and abstract of these publications, a total of 829 articles were chosen for the next step.

The second step was an individual review for the full-text of the selected articles, in order to include articles that explored the IFs among various sustainability indicators. In this step, the terms added as search codes when referring to the aforementioned 10 types of IFs were: "green wall", "breathing façade", and "living wall" for VGS; double-skin perforated façade with the term "DSPF" and "ventilated façade" for DSF; "cushion façade" and "membrane cladding" for ETFE; "micro-algal façade" and "photobioreactor panel" for PBR; "fluid glass" and "water flow glazing" for BIST; "adaptive building envelope" and "kinetic façade", and "climate adaptive building shells" for auto-blinds; and finally, "switchable glazing", "suspended particle devices", and "electrochromic" for electro-active façade systems. 815 articles fit this review purpose.

In the final PRISMA step, investigators extracted all required information for the next steps of research article from those 815 remaining articles selected. Fig. 1 presents the PRISMA flowchart.

Phase 3. Classification

The following sections classify the selected studies according to their IF type, content, year of publication and methodology.

IF type

Fig. 3 shows the number of publications regarding each IF type. As depicted, VGS technology is the major investigated IF type with more than 190 publications. The second most studied IF system is BIPV with defined 137 documents. Electro-active, BIST, and DSF systems have each been investigated in 100 publications. Auto-blind façade, ETFE, PBR, and TiO_2 have from 60 to 80 research documents for each IF, while wind wall has been investigated in 25 publications.

Sustainability contents in IF publications

From the 16 sustainability indicators this review selected, as shown in Fig. 4, the energy-saving indicator with more than 400 publications was the most investigated. Energy efficiency and flexibility indicators have been considered in more than 200 publications since 2010. However, the review found a lower number of publications regarding reusability and dismantling costs for IFs as these are relatively new in the IF sustainability course.

Publication year

During 2015, there were 120 publications about sustainability performances generated for IF, while the review found fewer than 80 in the previous years from 2010 to 2014. In 2016 this number increased by 150 publications, which from those the impacts by VGS, PBR, BIPV, BIST, and auto-blinds in building sustainability performances were the most popular research studies. Fig. 5 presents these trends evolution process from 2010 to 2020, with their results divided on IF types. As shown in Fig. 5, since 2017, the number of IF sustainability studies focusing on the 10 studied in-depth façades has started to decrease. A general analysis of the reviewed studies concluded that, since 2017, researchers switched to study newly emerging IF technologies instead of the 10 IFs reviewed in the present article. Moreover, by then, these 10 IFs had already been studied from numerous points of view in numerous publications so there were fewer gaps to be filled. These are the two main reasons for this downturn.

Applied methodologies

The methodologies used in the studied literature were review, experimental, simulation, and survey methods, as well as combinations of them. From the main groups of well-known methodologies, the experimental–numerical method with 279 (40%) applications was the most commonly used methodology in the studied literature. Followed by 115 (15%) review articles, 111 (15%) numerical researches, and 109 (14%) experimental methodologies. As presented in Fig. 6, more than 50% of VGS and DSF-related studies – the most investigated IF types – were carried out using the experimental–numerical methodology. Moreover, IF types with lower published literature like bio-reactor or BIPV, have been studied using review, numerical, experimental, and experimental–numerical methodologies respectively.

Phase 4. Analyses

The following sections analyze the studied literature contributions on IF advancements. This analysis is organized according to the three sustainability pillars and the 16 considered indicators, as depicted in Table 2.

Economic

As already depicted in Fig. 1, the economic requirement was the least analyzed pillar of sustainability in the reviewed literature. Economic indicators were investigated in 132 IF publications, with the terms *IF1-Fabrication and assembling cost, IF2-Maintenance cost, IF3-Operation cost,* and *IF4-Dismantling cost*. Fig. 7 depicts the studied frequency for each economic indicator in publications during the last decade. As shown, since early 2010, these publications had investigated IF economic performance. However, indicators *IF2-Maintenance cost* and *IF4-Dismantling cost* before 2014 were rarely analyzed, while since then, research activity on all economic indicators has considerably increased. The distribution of contents also reveals that there is still a need to provide content with specified values on the economic performance by IF technologies.

From the analyzed indicators, *IF1-Fabrication and assembling cost* with 57 identified publications (42%) has been considered as one of the main issues studied by researchers since the early stages of IF development. In particular, Attia et al. [44] with an analytical survey, realized that for most participants, the fabrication cost is one of the main barriers in IF development. Wilkinson et al. [45] explained that with innovation, the evolution of design and technology, and economies of scale, the production cost of IFs can fall and will have long-term cost savings. Tam et al. [6], Böke et al. [16], and Ahmed et al. [32] have reported the net fabrication and assembling costs for various IF systems. V. John [46] expressed that introducing new independent systems with less complexity will contribute to their performances in economic indicators. Other studies listed the components and equipment of different IF technologies and their yearly surplus or deficit which mainly have criticized the high prices of this equipment. Bertram et al. [47] have presented an "economic façade" with the idea of common modular building vertical skins. This modularity in some IFs such as VGS, DSF, TiO_2 tile, ETFE, and BIPV, have reduced their production and assembly cost and time. While Wong et al. [48] criticized the initial cost of VGS, by showing more than 70% of user's and developer's dissatisfaction, comparing typical façade materials. Pan et al. [49] identified that the time-effective installation and maintenance process should be considered as the main issue on IF developments.

As presented in Fig. 7, since 2014 most economic-related studies (34%) have focused on the maintenance cost of IFs during their whole life cycle. From those studies, many [50-52] have proposed ETFE systems as much more cost-efficient IF due to their modularity and resulted in rapid assembling and maintenances processes. In addition, researchers have suggested the application of TiO_2-SiO_2-containing material on IFs for reducing maintenance cost by less water consumption and fewer detergents contamination [53]. Several studies have criticized the required high maintenance cost of IFs [54-56] while others have provided comments regarding regular inspection, cleaning, and replacement frequency in each year or the whole life cycle [57,58].

Fig. 7 shows that, during the last decade, some publications (15%) have also investigated the operational costs of IF technologies. These include studies on input energy costs for motion [59-61], energy for collect, transfer, and record information [62,63], and the required supplements during whole life span [64]. Other documents have also provided information on the zero or nearly-zero operational cost of some IF technologies as DSF [65] and TiO_2 façades [57]. However, other studies have highly criticized the required high amount of energy and/or supplements by some IF alternatives [8].

As depicted in Fig. 7, fewer studies (7%) have investigated the dismantling and reconstruction cost of IFs and their consequent bills [51,66], resources consumption [67], and waste generation [68].

As presented in the above paragraphs, IF economic performances had been investigated from various points of view and values, which make them difficult to compare. In rare cases, the authors preferred treating economic aspects in different ways. For example, Attia et al. [34] highlighted business opportunities in the IF sector through surveys of organizations operating in this sector.

Fig. 8 illustrates the distribution of the economic-related studies considering their content, including provided values, commentaries, critiques, or praises (see step 4.1). The difference in the distribution of studies between critiques and praises shows that IF technologies are still economically not acceptable and need deeper investigations. Table E1, E2, E3 and E4 in Appendix E present the economic performance of various IF technologies from different points of view in the reviewed literature.

Environmental

This review considers the environmental pillar as a major sustainability dimension, which deals with limited resources, generated waste, and emissions mainly during the (i) production, (ii) use, and (ii) end of life cycle phases of buildings. As shown in Fig. 1, the environmental performance by IFs, with 407 identified publications, is the most considered requirement in the studied documents. The identified publications include seven different environmental indicators that have been distributed as (i) *I5-EE* (7%), (ii) *I6-EC* (5%), (iii) *I7-Annual energy saving* (44%), (iv) *I8-Energy conversion efficiency* (22%), (v) *I9-Annual sequestered emission* (14%), (vi) *I10-Recyclability* (5%), and (vii) *I11-Reusability* (1%). Fig. 9 presents the number of studies regarding each of the seven indicators in the analyzed documents from 2010 to 2020.

Fig. 9 illustrates that by early 2010, 182 studies had investigated the IF main contributions to buildings' energy consumption. Accordingly, the *I7-Energy-saving* indicator has the highest influence on IF environmental performance. Asadian et al. [69] declared energy saving as one of the main goals of IF application. Nicoletti et al. [70], Biloria et al. [71], and Tang et al. [72] outlined major energy-saving considerations in the IF development process as being materials used, automation systems, operation patterns, and structural simulations. While Negev et al. [73], Tudiwer et al. [74], and Wang et al. [75] highlighted other important IF-related energy-saving parameters to be U-value, G-value, heat losses, and amount of light and shading.

IF technology also contributes to the partial or overall energy consumed by a building while producing energy [31]. *I8-Energy conversion efficiency* analyzes the ratio between the output and input energy in IF technologies during their use phase. Among the identified literature, 87 publications deal with this indicator, which is the second most investigated environmental indicator. Referring to these publications, this ratio in alternatives IF2-DSF and IF8-TiO_2 façade is neutral. In alternatives IF4-Wind wall, IF5-PBR, IF6-BIPV, and IF7-BIST this ratio is positive, while in alternatives IF1-VGS, IF3-ETFE, IF9-Auto-blinds, and IF10-Electroactive this ratio is negative. As shown in Fig. 9, since 2015, researchers have analyzed this indicator mainly concluding about its lower efficiency in some IF cases [76,77]. Nevertheless, Capezzuto [78] by evaluating the ETFE cushion façade, stated that one inflation unit can feed a façade ranging from 1400 to 2325 m^2 with a power consumption of less than 1 kW. Karanouh et al. [79] analyzed the Al-Bahar tower auto-blinds and presented that its mechanism is driven by a centrally positioned electric screw-jack linear actuator that operates on much less energy than a regular light bulb. Other studies, foreseeing that future IF technologies will have higher conversion efficiency, have proposed new integral IFs which integrate wind turbines inside DSF tunnel [80], BIPV/T-DSF systems [81], auto-blind and electrochromic setup [82], or the incorporation of PCMs or SMAs in wind walls and Electro-active glazing [83].

This literature review has found *I9-Annual sequestrated emission* as another highly investigated indicator, with 49 publications from 2010 to 2020. These studies have highlighted three approaches for reducing emissions by IF technologies as (i) active or passive absorption of emissions, (ii) generating energy, and (iii) saving energy. In each IF technology, these three approaches provide different sequestration values considering the type of generated energy and the absorption process or a combination of both. Seeking other parameters on carbon sequestration performances by IF technologies, Bryan et al. [84] stated that the amount of CO_2 sequestration by IF depends on its design, its surface area, the height of the building, and the climate conditions at that particular site. Referring to studies by Topličić-Ćurčić et al. [85], Shukla et al. [86], and Haghir et al. [87] photocatalytic TiO_2 paints and PBR panels are pioneering technologies in terms of active sequestration of CO_2 and other chemical pollutants. This review also shows that VGS, Auto-blinds, Electro-active, DSF, ETFE, BIPV, and BIST façades are actively contributing to reducing emissions from 15% to 60% respectively.

The rest of the environmental indicators – *I5-EE, I6-EC* and, *I10-Recyclability* – have been studied in 32, 27 and 21 documents respectively. This review has extracted the consumed energy and embodied emissions in the IFs production process through these publications. As presented in Fig. 9, since the early years of the last decade, investigations have focused on EC of IF systems, which later – since 2014 – researchers also studied the EE of IF systems. In most cases, the identified studies have outlined the high risk of EE and EC in the IF production, referring to the increase of environmental burdens rather than a decrease. EC in some IF cases constitutes a significant portion of construction greenhouse gas (GHG) emissions [88]. Oquendo-Di et al. [89] analyzed that the manufacturing phase accounts for 90–95% of VGS total environmental impacts. While Salah and Romanova [90] outlined that the production of IF1-VGS supplements as structure, inverters, cables, or controllers, produces high emissions levels. On the other hand, some studies have proposed new low-emission IF production solutions. Almusaed et al. [91], Khoshnava et al. [92], Price [93] proposed substituting the use of steel or PVC for ecological materials that can save 69.9% of EE. Silva et al. [94] showed that to reduce the impacts of biomass production, PVC and steel utilization need to be minimized. TiO_2 production also causes extensive environmental impacts, which could be avoided by recently emerging hydrometallurgical processes. A novel approach featured alkaline roasting of titania slag (ARTS) – with its subsequent washing, leaching, solvent extraction, hydrolysis, and calcination stages – to minimize EE of TiO_2 [95]. While Huang and Yu [96] analyzed significant emission of BIPV production process during purification, crystallization, slicing of the silicon, and battery production. To further reduce the associated environmental burden, Robinson-Gayle et al. [97] presented ETFE foil membranes as an eco-friendly solution in terms of emissions. Nevertheless, an analytical study resulted that the high EC of IF systems is recoverable within their first operation year [98].

The potential recyclability percentage in IF technologies is another solution to reduce their EE and EC during their manufacturing process. Recycling will also contribute to municipal waste management practices that recently have faced serious challenges [99]. In this regard, Crespi and Persiani [100] outlined that adopting appropriate management policies in IF waste is essential in terms of separation, transportation, disposal, and landfilling of their waste. This literature review has found out that a significant percentage of studied IF alternatives is recyclable. Including VGS with 100% [101], ETFE with 100% [102,103], BIPV with 95% [104], and TiO_2 with 90% [105] recycling percentages. However, according to research conducted by Fashrion et al. [106], some IF wastes also can pose a risk to social sustainability.

In environmental requirement studies, *I11-Reusability* is less investigated although it has a great impact. This review could not find more than five studies on IF reusability investigations. Since 2014, these studies have proposed reusing as a step above recycling and an efficient approach for reducing IFs' environmental loads [107,108]. However, reusing waste in the construction sector is practically new, and the identified studies highlight those greater efforts are required to put on the end-of-life of IF materials. Foster [109] outlined that designing a building façade to support adaptation and reuse can reduce waste and extend its useful life, providing economic and environmental benefits for builders, owners, occupants, and the communities. Galanakis et al. [110] stated that this practice also avoids building removal together, and allows materials to be quickly and cost-effectively taken apart.

Fig. 10 depicts that most of these studies cover the specific value issue on these environmental indicators chiefly since 2014. Furthermore, numerous studied publications have provided great comments and solutions for IFs' environmental loads during their fabrication, use, and their end-of-life phases. The remaining studies have criticized IFs' negative environmental impacts while others have praised their emission recovering time after launching to operate. Table F1, F2, F3, F4, F5, F6 and F7 in Appendix F illustrate the main identified values comments critiques and praises in the reviewed literature.

Social performance

Social topics have been investigated in 267 publications. This section studies these social publications focusing on the five following indicators: (i) *I12-Fabrication and assembling ease* (13%), (ii) *I13-Flexibility* (37%), (iii) *I14-Ventilation performance* (12%), (iv) *I15-Light performance* (25%), and (v) *I16-Safety* (11%).

As depicted in Fig. 11, since 2011, *I13-Flexibility* is the most frequently studied indicator, being analyzed in more than 100 publications. The term "flexibility" refers to each IF potential in the continuous adaptation of its layout and configuration to evolving requirements. This review found that in most cases, IFs are flexible technologies considering their provided (i) aesthetic value [111-114], (ii) property values [115], (iii) facilities [86,116], (iv) resistance [57,117], or (v) adjustability [71,118-120]. In line with other flexibility aspects of IFs, Lamnatou et al. [121] declared that the VGS façade reduces long-term noise annoyances and stress-related psychosocial symptoms. This review also found studies on IFs' flexibility flaws. For instance, reduction of rentable space, overheating and increased construction weight in DSF [122], acoustic pollution in Wind-wall [123], and the slow switching cycle in electro-active façade, are some of these weaknesses in terms of IFs flexibility.

The light performance by IFs (*I15*) is the second most frequent indicator in social requirement. Since 2010, this indicator has been analyzed in 65 social documents that present IFs' great importance in ambient light conditions and subsequent influence on users. Part of these publications have evaluated IFs light performance considering users' visual perception parameters, such as colorfulness, complexity, naturalness, and light [76,124,125]. For instance, a survey conducted on an Australian council house kinetic façade showed that this IF provides views for 80% of its occupants [126]. Another study demonstrated that PBR system met the illuminance requirement for an office building [127]. More technical studies on light performance have evaluated solar transmittance, shading effect, glare, and transparency [128,129]. This review highlights the following findings: (i) IF1-VGS lowers daylight illuminance level [130], (ii) IF2-DSF reduces the natural light transmission [115], (iii) IF3-ETFE offers 95% light transmission [121], and (iv) IF7-BIST offers 84% solar transmission [114].

The remaining 100 reviewed publications focus on indicators *I12*, *I14*, and *I16* with a similar distribution. Since 2010, these studies mainly outlined that IF projects involve innovative technologies, while expanding them as user-friendly technologies is a challenging task with relatively high risks. For instance, developers in the application of some IF cases, tend to take conservative attitudes due to the associated risks, their assembling time, and required professionals [131]. This review identified IF2-DSF [132,133], IF5-PBR [13], IF6-BIPV [61], IF7-BIST [134], and IF10-Electroactive [135] façades as sophisticated technologies in terms of design, fabrication, implementation, simulation, reparation, and replacement. While Elgizawy [136] declared that the modular VGS has the easiest assembly, dismantling, and maintenance processes. ETFE structures are also easy to fabricate, fast to erect and they can avoid the need for scaffolding and large cranes [52].

In line with previous studies, this review concludes that safety-based design is also a crucial consideration among the decision-makers in terms of fire resistance, toxicity, and user wellness. For instance, developing PBR without intensive precautions can cause health impacts by leakage or damage [137]. Furthermore, designing and developing DSF without preventing strategies such as fire and smoke spread is highly risky [138]. This literature review shows that façade developers had avoided these risks in IF1-VGS, IF3-ETFE, IF6-BIPV, IF7-BIST, and IF8-TiO_2 façades. Akrami and Habibi [139] in a case study within the Turkish context, highlighted the positive social effects of VGS on the stress and recovery rate of patients in health centers.

VGS also offers ventilation as it reduces the need to extract and filter fresh air [140]. Researchers have investigated this feature of IFs by different means of CFD simulations, surveys, or CO_2 concentration analyses. Less common studies also conducted were those for odors, dust, and ashes. Loftness et al. [141] explained that natural ventilation is a method to supply fresh air by means of passive forces, typically by wind speed and direction or differences in pressure internally and externally. In different IF alternatives, natural ventilation can be achieved by various approaches. Reducing humidity by IF1-VGS [18], providing buffer zone by IF2-DSF [142] and IF3-ETFE [143] and IF6-BIPV [144] systems, and purifying air by IF8-TiO_2 [53] and IF5-PBR [145] façades are some of these approaches. This review found DSF to achieve the highest ventilation performance by providing natural ventilation during about 60% of the year [146].

Fig. 12 depicts that IFs are socially acceptable technologies with 45% of the praises among social studies. However, because of the qualitative nature of social indicators, they differ significantly concerning their economic and environmental indicators. This review only found 31 documents (10%) that have provided specific values on the social performance by IFs. These documents have mostly simulated ventilation and lighting performances by IFs. Among other documents, 80 publications (30%) have criticized IFs' low social performances, while the remaining 15% provided comments on human well-being, comfort, and labor safety. Table G1, G2, G3, G4 and G5 in Appendix G present crucial examples of these values, critiques, praises and comments.

In general, this social analysis shows that social acceptance is a condition that can differ based on different perspectives, climates, cultures, or locations. More importantly, this review confirms that there is no consensus on the social evaluation methods. To sum up, researchers have also found that, despite fewer publication trends on safety indicators, IF technologies have provided maximum safety for tenants.

Future research directions

As a continuity for knowledge production in the field [147], this review proposes new studies that rely on the evaluation of the analyzed literature and the respective identification of main research gaps. Table 3 presents 12 research directions to guide decision-makers on the introduction of sustainability practices in the IF development scenario regarding the three main sustainability branches.

Considering the current research scenario and the proposed framework, this review groups new research directions in three categories:

1. Better clarify IF sustainability concepts to raise stakeholders' awareness on the importance of energy consumption, carbon reduction, waste reduction, and their responsibilities in chains and material flows.
2. Incorporate more comprehensive decision-making systems in project planning processes by considering all phases in the life-cycle assessment (LCA), life cycle costing (LCC), and social issues.
3. Consider policies regarding taxation, legal frameworks, specific recycling targets, business responsibility, and regulations in building codes.

One of the major problems is the lack of awareness about IF sustainability among all stakeholders, from construction workers to users, including industry and contractors among others [148]. These involved groups in the IF development process require a mentality change regarding sustainability potentials for IF technologies. For instance, the lack of interest to design IF products for dismantling and reuse at the end of their lives is a significant challenge. The implementation of these principles in design processes requires support by public agencies, as well as new knowledges, tools, and guidance. Another issue is related to the few multi-criteria decision-making (MCDM) sustainability analyses. Most literature mainly focuses on maximum energy saving, lighting comfort and ventilation performances. Accordingly, numerous values involving maintenance, operation, fabrication, assembling and safety need to be more engaged.

Conclusion

This study has successfully reviewed publications from 2010 to 2020 focusing on the sustainability of IF technologies regarding 16 main indicators. SLR and PRISMA techniques have carried out this state of the art methodology systematically. Despite the growing research activity in the IFs sustainability field, this research area is still in the exploratory phase, without a confirmatory holistic approach that involves the three pillars of sustainability. This integral approach would assist in the improvement and advancement of sustainable production in various sectors of the economy, environment, and society; as has been confirmed in the case of façades development [14,149].

Numerical findings from the literature reviewed for this study have been normalized and clustered around the aforementioned 16 indicators. These findings have been presented in 16 Tables with extracted relevant values for each IF alternative. These tables helped identify existing trends and areas for further research. Overall, the proposed framework has clarified a holistic perspective of the potential sustainability contributions by IFs in the built environment for all stakeholders with an interest in IF – especially practitioners and researchers.

The thematic axis shows that the main trend in this area is energy-saving by IFs. The axes also highlight the popularity of VGS and BIPV façades among researchers and the need for more investigation on some other alternatives. Regarding the methodologies used in IF studies, a main approach used is *experimental + numerical methodology*, chiefly through LCA data and in a few through LCC data. Nevertheless, there is still a need for a new standardized approach for analyzing both data and results and other factors all together that can be an opportunity for future studies.

In terms of this research project's limitations, the following aspects need to be considered: (i) documents studied are more focused on academic research than in the construction industry; (ii) literature sample exclusively includes articles published in English; (iii) articles analysis was mainly manual, through the reading of titles, abstracts, and keywords. This type of procedure could involve unintentional bias in the analysis of the selected works. Nevertheless, despite these limitations, the results of this literature review bring scientific contribution related to sustainability and application studies for IF alternatives. Accordingly, this review has perceived that sustainability assessment is crucial in the search for IF production, which through it the capability to optimize their performance, services, and processes becomes possible.

In general, IFs should be seen as long-term projects and all intangible costs and maintenance should be addressed at the conceptual stage. Awareness about how the system works and acceptance of the complexities and potential disadvantages are therefore important to explore. Nevertheless, recent technologies and advancements in sustainable construction research projects tend to be more cost-effective, aiming at adopting reusable, zero-carbon, zero-waste, and safe technologies.

CRediT authorship contribution statement

Saeid Habibi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Oriol Pons Valladares:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Diana Maritza Peña:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Protocol used to select the most representative IF systems.

Table A1
Point system for the qualification of IF types.

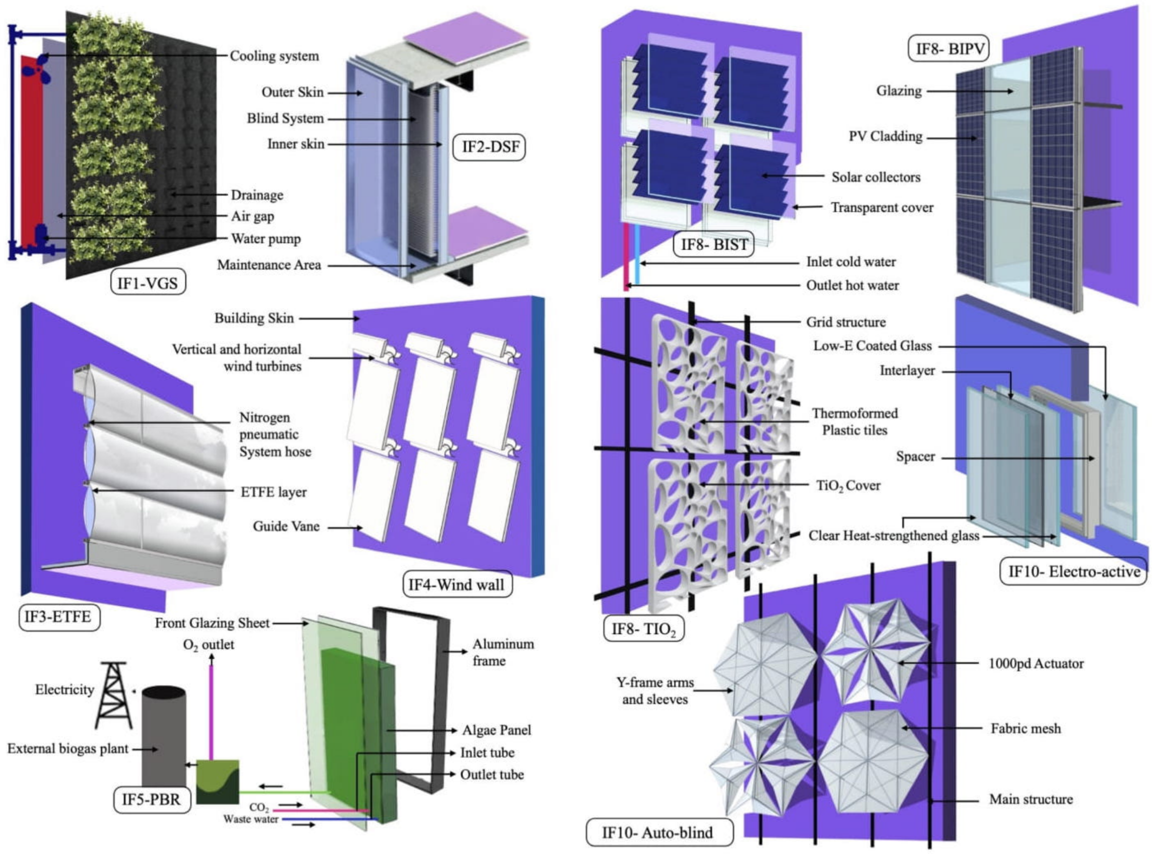
Functions	Parameters	Value	Points
Visual performance	Maximize daylight	MD	2
	Minimize glare	MG	1
	Provide view	V	1
Thermal performance	Provide fresh air	FA	1
	Control humidity	CH	1
	Circulate air	CA	1
	Control radiation	CR	2
Energy performance	Incorporate insulation	I	1
	Collect heat	CoH	2
	Reject heat	RoH	1
	Energy generation	EG	3
Acoustical performance	Attenuation of sounds	AS	1
Environmental performance	Sequestrate emissions	SE	1
	Absorb emissions	AE	3
Added value performances	Provide aesthetic value	PA	1
	Provide safety	PS	1
	Increase property value	IV	1

Appendix B. 16 established sustainability assessment indicators with multi-disciplinary experts and their functions.

Table B1
The functions of each indicator in previously developed MIVES sustainability assessment tool.

	Function
I1	In literature, analyzes the manufacturing and assembling cost for the VGS system in €/m^2.
I2	Looks at DSF systems maintenance cost, including cleaning and regular inspection costs, in €/m^2/annually.
I3	In literature, seeks the cost for the annual energy consumed by the membrane cladding for its own operation in €/m^2, disregarding energy which can be saved or generated.
I4	Is associated with the end-of-life criteria and searching the deconstruction and demolition costs of wind wall systems in €/m^2 in literature.
I5	Looks for the amount of energy required to manufacture and assemble of the bio-reactor systems in kWh/m^2.
I6	In the literature, searching for the EE of the BIPV in CO_2/m^2.
I7	Considers the energy that can be saved in kWh/m^2/annually. This indicator, in the literature investigates the U-value and R-value of BIST systems.
I8	Is the energy conversion efficiency which evaluates the ratio between the useful output and input energy of TiO_2 façade system during the usage phase, in kWh/m^2/annually.
I9	Considers the sequestered emissions by saving and/or generating energy by Kinetic façade system in CO_2/m^2/annually.
I10	Investigates the recyclability rate of electro active system in literature.
I11	Searches the reusability rate of ETFE system in literature.
I12	Reviews the value of VGS system in their production and assembling ease.
I13	Explores the ability for handling change in DSF system and repercussion based on their novelty, appearance, reliability, and popularity.
I14	Evaluates the provided fresh air and natural ventilation of BIPV system in literature.
I15	Searches the accessed favorable natural light based on its transparency level and ability to prevent glare.
I16	Looks for the safety level of each IF being as fire resistance, durability, and other possible risks in literature.

Appendix C



Appendix C. The following figures illustrates the details of qualified 10 IF alternatives.

Appendix D. 160 search codes generated through the combination of the newly developed MCDM sustainability assessment model and the most representative IF technologies and their relevant values.

Table D1
Generated search codes and their relevant values.

Code	Relevant value	Code	Relevant value	Code	Relevant value
I1 + IF1 = SC1	Fabrication cost of VGS	I6 + IF6 = SC56	Embodied carbon of BIPV	I12 + IF1 = SC111	Fabrication ease of VGS
I1 + IF2 = SC2	Fabrication cost of DSF	I6 + IF7 = SC57	Embodied carbon of BIST	I12 + IF2 = SC112	Fabrication ease of DSF
I1 + IF3 = SC3	Fabrication cost of ETFE	I6 + IF8 = SC58	Embodied carbon of TiO_2 façade	I12 + IF3 = SC113	Fabrication ease of ETFE
I1 + IF4 = SC4	Fabrication cost of wind-wall	I6 + IF9 = SC59	Embodied carbon of auto-blinds	I12 + IF4 = SC114	Fabrication ease of wind-wall
I1 + IF5 = SC5	Fabrication cost of bioreactor	I6 + IF10 = SC60	Embodied carbon of electro-active	I12 + IF5 = SC115	Fabrication ease of bioreactor
I1 + IF6 = SC6	Fabrication cost of BIPV	I7 + IF1 = SC61	Energy saving by VGS	I12 + IF6 = SC116	Fabrication ease of BIPV
I1 + IF7 = SC7	Fabrication cost of BIST	I7 + IF2 = SC62	Energy saving by DSF	I12 + IF7 = SC117	Fabrication ease of BIST
I1 + IF8 = SC8	Fabrication cost of TiO_2 façade	I7 + IF3 = SC63	Energy saving by ETFE	I12 + IF8 = SC118	Fabrication ease of TiO_2 façade
I1 + IF9 = SC9	Fabrication cost of auto-blinds	I7 + IF4 = SC64	Energy saving by wind-wall	I12 + IF9 = SC119	Fabrication ease of auto-blinds
I1 + IF10 = SC10	Fabrication cost of electro-active	I7 + IF5 = SC65	Energy saving by bioreactor	I12 + IF10 = SC120	Fabrication ease of electro-active
I2 + IF1 = SC11	Maintenance cost of VGS	I7 + IF6 = SC66	Energy saving by BIPV	I13 + IF1 = SC121	Flexibility of VGS
I2 + IF2 = SC12	Maintenance cost of DSF	I7 + IF7 = SC67	Energy saving by BIST	I13 + IF2 = SC122	Flexibility of DSF
I2 + IF3 = SC13	Maintenance cost of ETFE	I7 + IF8 = SC68	Energy saving by TiO_2 façade	I13 + IF3 = SC123	Flexibility of ETFE
I2 + IF4 = SC14	Maintenance cost of wind-wall	I7 + IF9 = SC69	Energy saving by auto-blinds	I13 + IF4 = SC124	Flexibility of wind-wall
I2 + IF5 = SC15	Maintenance cost of bioreactor	I7 + IF10 = SC70	Energy saving by electro-active	I13 + IF5 = SC125	Flexibility of bioreactor
I2 + IF6 = SC16	Maintenance cost of BIPV	I8 + IF1 = SC71	Energy efficiency of VGS	I13 + IF6 = SC126	Flexibility of BIPV
I2 + IF7 = SC17	Maintenance cost of BIST	I8 + IF2 = SC72	Energy efficiency of DSF	I13 + IF7 = SC127	Flexibility of BIST
I2 + IF8 = SC18	Maintenance cost of TiO_2 façade	I8 + IF3 = SC73	Energy efficiency of ETFE	I13 + IF8 = SC128	Flexibility of TiO_2 façade
I2 + IF9 = SC19	Maintenance cost of auto-blinds	I8 + IF4 = SC74	Energy efficiency of wind-wall	I13 + IF9 = SC129	Flexibility of auto-blinds
I2 + IF10 = SC20	Maintenance cost of electro-active	I8 + IF5 = SC75	Energy efficiency of bioreactor	I13 + IF10 = SC130	Flexibility of electro-active
I3 + IF1 = SC21	Operation cost of VGS	I8 + IF6 = SC76	Energy efficiency of BIPV	I14 + IF1 = SC131	Ventilation by VGS
I3 + IF2 = SC22	Operation cost of DSF	I8 + IF7 = SC77	Energy efficiency of BIST	I14 + IF2 = SC132	Ventilation by DSF
I3 + IF3 = SC23	Operation cost of ETFE	I8 + IF8 = SC78	Energy efficiency of TiO_2 façade	I14 + IF3 = SC133	Ventilation by ETFE
I3 + IF4 = SC24	Operation cost of wind-wall	I8 + IF9 = SC79	Energy efficiency of auto-blinds	I14 + IF4 = SC134	Ventilation by wind-wall
I3 + IF5 = SC25	Operation cost of bioreactor	I8 + IF10 = SC80	Energy efficiency of electro-active	I14 + IF5 = SC135	Ventilation by bioreactor
I3 + IF6 = SC26	Operation cost of BIPV	I9 + IF1 = SC81	Sequestrated emission by VGS	I14 + IF6 = SC136	Ventilation by BIPV
I3 + IF7 = SC27	Operation cost of BIST	I9 + IF2 = SC82	Sequestrated emission by DSF	I14 + IF7 = SC137	Ventilation by BIST
I3 + IF8 = SC28	Operation cost of TiO_2 façade	I9 + IF3 = SC83	Sequestrated emission by ETFE	I14 + IF8 = SC138	Ventilation by TiO_2 façade
I3 + IF9 = SC29	Operation cost of auto-blinds	I9 + IF4 = SC84	Sequestrated emission by wind-wall	I14 + IF9 = SC139	Ventilation by auto-blinds
I3 + IF10 = SC30	Operation cost of electro-active	I9 + IF5 = SC85	Sequestrated emission by bioreactor	I14 + IF10 = SC140	Ventilation by electro-active
I4 + IF1 = SC31	Dismantling cost of VGS	I9 + IF6 = SC86	Sequestrated emission by BIPV	I15 + IF1 = SC141	Lighting by VGS
I4 + IF2 = SC32	Dismantling cost of DSF	I9 + IF7 = SC87	Sequestrated emission by BIST	I15 + IF2 = SC142	Lighting by DSF
I4 + IF3 = SC33	Dismantling cost of ETFE	I9 + IF8 = SC88	Sequestrated emission by TiO_2 façade	I15 + IF3 = SC143	Lighting by ETFE
I4 + IF4 = SC34	Dismantling cost of wind-wall	I9 + IF9 = SC89	Sequestrated emission by auto-blinds	I15 + IF4 = SC144	Lighting by wind-wall
I4 + IF5 = SC35	Dismantling cost of bioreactor	I9 + IF10 = SC90	Sequestrated emission by electro-active	I15 + IF5 = SC145	Lighting by bioreactor
I4 + IF6 = SC36	Dismantling cost of BIPV	I10 + IF1 = SC91	Recyclability of VGS	I15 + IF6 = SC146	Lighting by BIPV
I4 + IF7 = SC37	Dismantling cost of BIST	I10 + IF2 = SC92	Recyclability of DSF	I15 + IF7 = SC147	Lighting by BIST
I4 + IF8 = SC38	Dismantling cost of TiO_2 façade	I10 + IF3 = SC93	Recyclability of ETFE	I15 + IF8 = SC148	Lighting by TiO_2 façade
I4 + IF9 = SC39	Dismantling cost of auto-blinds	I10 + IF4 = SC94	Recyclability of wind-wall	I15 + IF9 = SC149	Lighting by auto-blinds
I4 + IF10 = SC40	Dismantling cost of electro-active	I10 + IF5 = SC95	Recyclability of bioreactor	I15 + IF10 = SC150	Lighting by electro-active
I5 + IF1 = SC41	Embodied energy of VGS	I10 + IF6 = SC96	Recyclability of BIPV	I16 + IF1 = SC151	Safety of VGS
I5 + IF2 = SC42	Embodied energy of DSF	I10 + IF7 = SC97	Recyclability of BIST	I16 + IF2 = SC152	Safety of DSF
I5 + IF3 = SC43	Embodied energy of ETFE	I10 + IF8 = SC98	Recyclability of TiO_2 façade	I16 + IF3 = SC153	Safety of ETFE
I5 + IF4 = SC44	Embodied energy of wind-wall	I10 + IF9 = SC99	Recyclability of auto-blinds	I16 + IF4 = SC154	Safety of wind-wall
I5 + IF5 = SC45	Embodied energy of bioreactor	I10 + IF10 = SC100	Recyclability of electro-active	I16 + IF5 = SC155	Safety of bioreactor
I5 + IF6 = SC46	Embodied energy of BIPV	I11 + IF1 = SC101	Reusability of VGS	I16 + IF6 = SC156	Safety of BIPV
I5 + IF7 = SC47	Embodied energy of BIST	I11 + IF2 = SC102	Reusability of DSF	I16 + IF7 = SC157	Safety of BIST
I5 + IF8 = SC48	Embodied energy of TiO_2 façade	I11 + IF3 = SC103	Reusability of ETFE	I16 + IF8 = SC158	Safety of TiO_2 façade
I5 + IF9 = SC49	Embodied energy of auto-blinds	I11 + IF4 = SC104	Reusability of wind-wall	I16 + IF9 = SC159	Safety of auto-blinds
I5 + IF10 = SC50	Embodied energy of electro-active	I11 + IF5 = SC105	Reusability of bioreactor	I16 + IF10 = SC160	Safety of electro-active
I6 + IF1 = SC51	Embodied carbon of VGS	I11 + IF6 = SC106	Reusability of BIPV		
I6 + IF2 = SC52	Embodied carbon of DSF	I11 + IF7 = SC107	Reusability of BIST		
I6 + IF3 = SC53	Embodied carbon of ETFE	I11 + IF8 = SC108	Reusability of TiO_2 façade		
I6 + IF4 = SC54	Embodied carbon of wind-wall	I11 + IF9 = SC109	Reusability of auto-blinds		
I6 + IF5 = SC55	Embodied carbon of bioreactor	I11 + IF10 = SC110	Reusability of electro-active		

Appendix E. Table E-1 presents the fabrication and assembling cost for different IF alternatives considering their equipment and production scale. Table E-2 presents in detail the maintenance cost of different IF alternatives available in literature. Table E-3 presents the operation cost of different IF alternatives. Finally, Table E-4 showing the dismantling cost of IFs and the main recovery potentials of their parts.

Table E1
Fabrication and assembling costs of different IF alternatives.

IF type	Ref	Year	Explanation	Relevant value
VGS	[150]	2013	Living wall system including all installation, plants, pot, dig, supporting systems and transportation costs.	214–659 €/m^2
	[151]	2015	Direct and indirect green façade.	less than75 €/m^2
	[152] [153]	20112019	a) Direct greening system (grown climbing plants). b) Indirect greening system (grown climbing plants + supporting material). c) Living wall system based on planter boxes HDPE. d) Living wall system based on foam substrate.	30–45 €/m^{2}40–75 €/m^{2}400–600 €/m^{2}750–1200 €/m^2
	[66]	2011	VGS systems including panels, supporting, plants and transport.	212,90 €/m^2
DSF	[154]	2013	Sydney	814.50 $/m^2
			Melbourne	798.50 $/m^2
			Brisbane	1085.50 $/m^2
			Adelaide	810.50 $/m^2
			Perth	914.50 $/m2
			Darwin	925.25 $/m2
	[112]	2011	Mechanical ventilated façade with juxtaposed modules in Belgium.	500–700 €/m^2
	[155]	2018	DSF including structural, material, and installation costs in Tehran.	1000–2200 $/m^2
ETFE	[52]		PTFE fiberglass membrane 0.38 mm thick.	3–5 $/m^2
	[103]	2016	0.127 mm thickness ETFE foil.	327 $/m^2
PBR	[156]	2017	1 m^2 for photo-bioreactor applications.	1000–1500 $/m^2
	[71]	2020	The cost of the BIQ house building façade was US	2200–2300 $/m^2
BIST	[114]	2017	For refurbishment projects with installation For new projects with installation	390 to 490 €/m^{2}600 €/m^2
	[157]	2012	BIST with evacuated tube BIST with glazed flat	500–100 €/m^{2}320–480 €/m^2
	[158]	2020	- Solar flat plate glazed collector including collector without water storage, overall hydraulic connections, pumps, control hardware and software. - Heat pipe vacuum tube collector including collector, anchoring brackets and channels, piping, temperature sensor without water storage, overall hydraulic connections, pumps, control hardware and software. - - Solar flat plate glazed collector including collector 2.32 m^2, anchoring brackets, piping, temperature sensor without water storage, overall hydraulic connections, pumps, control hardware and software.	250–300 €/m^{2}840 €/m^{2}535 €/m^2
TiO_2	[117]	2014	The value of TiO_2 pigment	1700–1900 $/t
	[159]	2015	In 2012 the cost exceeded of 70% over 12 years.	3.75 $/kg.
	[160]	2012	The PURETI coating application. The driveway protector (Seal-Krete) commercial water-based TiO_2 (CWB)	0.10 $/ft^{2}18.18 $/gallon10.70 $/m^2
Electro-active	[161]	2020	It was found that a market price reduction for architectural EC glazing would be necessary for the operational energy benefits to exceed the initial cost.	700 €/m^2
	[162]	2014	Commercially available products in SAGE™ and Gesimat.	1000 €/m^2

Table E2
Annual maintenance cost of different IF alternatives.

IF type	Ref	Year	Explanation	Relevant value
VGS	[18]	2014	Requires high maintenance and good irrigation system.	
	[163]	2013	The total maintenance cost for six various types of green façade being as Direct green façade, HDPE indirect green façade, steel indirect green façade, HDPE indirect with planter boxes, Steel indirect with planter boxes, living wall system with calculating all pruning, adjustments, irrigation, pipe replacements.	3 to 25 €/m^2
	[153]	2018	Maintenance costs for yearly pruning of green screen climbing plants.	2–5 €/m^2
	[66]	2018	Maintenance costs for living walls.	40–100 €/m^2
ETFE	[164]	2018	Just cleaning of the inside surface of the ETFE cushion may take place every 5–10 years but is rarely done due to the lack of necessity.	
PBR	[71]	2020	Require regular maintenance as it contains microorganism and need for keeping inside clean.	
	[165]	2017	Fouling has adverse effects on the algal processes such as increased cleaning frequency.	
BIPV	[166]	2019	The panels require cleaning every 2 months by sweet water.	
	[167]	2020	The annual repair cost was assumed to be 0.5% of the initial construction cost. The inverter replacement costs in January 2016 for the 466 PV modules.	38,591 $
	[168]	2020	The annual expense for maintenance is 0.5% of the initial investment.	
BIST	[169]	2020	Disadvantages include difficulty to access and maintain system.	
	[170]	2017	Possible solution to maintain is the use of multi-layered silica/titania (SiO_2/TiO_2) thin films.	
	[171]	2020	1.5% of initial investment on a yearly basis, in first year:Maintenance cost in 10th year:	150 cu233 cu
TiO_2	[172]	2013	Its super-hydrophilicity helps the cleaning process because it makes the surface dry faster, and prevent the undesirable water streaking or spotting on the surface.	
	[173]	2017	TiO_2 coating can address the current surge in façade maintenance cost and labor problems.	
Auto-blind	[126]	2015	Kinetic façade systems have high initial costs and need constant maintenance.	
	[174]	2019	Costly construction and maintenance.	
Electro-active	[174]	2016	All manufacturers indicate that the duration of these windows is between 20 and 30 years.	
	[120]	2018	Long-term durability and electrochemical cycling durability are the obvious criteria of EC.	
	[175]		These smart glasses do not often need replacing due to contamination or damage.	

Table E3
Annual operation cost of different IF alternatives.

IF type	Ref	Year	Explanations	Relevant value
VGS	[59]	2016	The whole life cycle operational energy required:	0 to 5466 MJ/m^2
ETFE	[55]	2012	A single inflation unit can pressurize about 1000 m2 of ETFE cushions and consists of two backward air foil blowers powered by electric motors. One of the motors is rated at 220 Watts and is permanently on standby while the other, rated at 100 Watts, only operates about 50% of the time using half as much energy as a domestic light bulb.	
PBR	[64]	2012	Studies have shown that algae can grow even in wastewater effluent.	
	[64]	2012	The estimated production costs of biomass for closed reactors.	2.95 $/kg
BIPV	[60]	2020	Operation cost.	41.39 €/kw
	[61]	2017	The annualized energy costs.	34.01 £/kWh.
	[176]	2020	The annual operation cost in January 2016	31,818 $/MW.
BIST	[63177]	2017	Energy costs (electricity for controller, pump) in first year	100 cu
		2014	Energy costs (electricity for controller, pump) in 10th year.	200 cu
Electro-active	[62]	2016	The authors estimate that a 1 m^2 SPD glazing panel consume	10.42 kWh/year

Table E4
Dismantling cost of different IF alternatives.

IF type	Ref	Year	Explanations	Relevant value
VGS	[178]	2019	The disposal stage costs the least across all 3 systems with the carrier system:The planter system at:The support system at:	35 $/m^{2}29 $/m^{2}13 $/m^2
	[66]	2018	Disposal cost of VGS for 155 m^2 façade calculated for.	0.90 €/m^2
ETFE	[179]	2018	ETFE weights 1/100th which can be entered in the ecological balance sheet at various points, for example in dismounting and disposal.	
	[51] [180]	20132019	The density of ETFE is approximately 1.75 g/cm^3 which provides fast, easy and cheap dismantling process.	
Wind wall	[181]	2017	Wind harvesting panels are demountable, making the building flexible in terms of use and appearance.	
BIPV	[182]	2019	BIPV dismantling is possible only by substituting them by equivalent building materials.	
TiO_2	[67]	2020	TiO2 particles deposited on the surface can easily be removed from the substrates.	
Auto-blind	[183]	2010	Kinetic architecture was supposed to be dynamic, adaptable and capable of being added to, reduced, or even being disposable.	

Appendix F. Table F-1 and F-2 present the EE and EC of the several IF systems. Table F-3 presents the annual energy saving by different IF alternatives. Table F-4 presents the energy conversion efficiency of various IF alternatives. Table F-5 shows the sequestrated emissions through different methods. Table F-6 proposes the recyclability of different IF alternatives in end-of-life phase. Finally, Table F-7 shows the recyclability of some IF cases found in literature.

Table F1
Embodied energy for different IF production and assembling process.

IF type	Ref	Year	Relevant value
VGS	[184]	2016	Living wall systems have EE of 743.05 to 2017 MJ/m^2 for initial material fabrication, 20.06 to 27.71 MJ/m^2 for transportation, 23.15 to 89.75 for assembling and construction.
	[185]	2013	1 m^2 of living wall using 47028 kJ/m^2 in manufacturing, and 0.19 kJ/m^2 in assembling process.
	[93]	2010	9772 sej/m^2/year energy required for manufacture and installation of 50 m^2 VGS.
DSF	[186]	2010	The total EE in the manufacture and production of Fully Glazed DSF is 2,480 MJ/m^2.
	[187]	2015	EE for the best configuration of the DSF is 2,273.08 MJ/m^2.
ETFE	[50]	2015	The EE during the cushion manufacturing phase is around 26.5 to 210 MJ/kg.
	[97]	2010	ETFE foils require minimal energy for production and installation.
	[188]	2015	1036.9 MJ/m^2 is the EE for ETFE cushion composed of 200 μm, 100 μm, 200 μm layers.
	[103]	2016	27 MJ/m^2 for a single layer of ETFE foils.
BIPV	[104]	2018	EE of 1238 MJ/m^2 for Amorf-Si, 1501 MJ/m^2 for Multi-Si and 1233 MJ/m^2 for CIGS types.
	[96]	2017	EE of 7460 MJ/m^2 for single-crystalline silicon and 2880 MJ/m^2 for amorphous silicon.
BIST	[189]	2016	Global energy requirement of 1.71 GJ for a unit of 1 m^2 (evacuated-tube collector).
TiO_2	[95]	2015	The sulfate method consumed 79 and 103 MJ/kg TiO_2 when ilmenite and slag were used as feeds, respectively, while the chloride method consumed 101 and 109 MJ/kg TiO_2 when synthetic rutile and slag were consumed, respectively.
	[95]	2015	The cumulative energy demand for the ARTS process is 92.6 MJ/kgTiO^2.
	[190]	2014	The average required EE of 1 kg titanium (Becher and Kroll processes) is 361 MJ.
Electro-active	[92]		EE per functional unit of EC glazes in 5 different benchmarks is between 30 and 37 MJ.

Table F2
Embodied carbon for different IF production and assembling process.

IF type	Ref	Year	Relevant value
VGS	[191]	2013	1 m^2 of VGS release 45.93 gCO_2 in manufacturing, and 0.05 g in assembling.
	[59]	2016	EC of VGS is between 88.27 and 147.28 $kgCO_2/m^2$ for initial material fabrication, 0.5 to 1.39 $kgCO_2/m^2$ for transportation, 2.81 to 5.92 $kgCO_2/m^2$ for assembling.
	[59]	2014	The 98 m^2 VGS configuration could bring the system's overall EC to 256 $kgCO_2$-eq per year, which includes 36.2 for plants production, 18.2 for plant treatment, 201.1 for structure.
DSF	[155]	2018	EC for 4 DSF alternatives being as Box, Shaft, Corridor and multi-story is varying from 460 to 556.5 $kgCO_2/m^2$.
	[192]	2012	EC from 650 to 900 $kgCO_2/m^2$ in 16 DSF configurations include glass and steel structure.
BIPV	[193]	2016	EC from 30 to 220 gCO_2 eq/kWh for BIPV system.
	[104]	2018	EC from 169.55 to 290.97 g CO_2-eq/kwh for thin film BIPV.
	[194]	2018	The 2.1 kWp BIPV system was estimated to have an embodied carbon of 4500 kg CO_2-eq (GWP, 100 years).
BIST	[189]	2016	Based on a functional unit of 1 m^2 (evacuated-tube collector), a global energy requirement of 1.71 GJ and a GWP of 101.2 kg CO_2-eq were presented.
TiO_2	[95]	2015	7.47 kg CO_2/kg TiO_2.
	[95]	2015	The total CO_2 emissions for the ARTS process is 7.47 kg CO_2/kg TiO_2.
Auto-blind	[195]	2015	A climate-adaptive façade has the EE of 60.5–73.3 Kg CO_2/m^2.

Table F3
The annual energy saving by IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[18]	2014	10% to 31% energy saving for reduced cooling loads due to the effect of greenery.
	[18]	2014	In hot climates, energy savings from 32% to 100% by VGS for cooling were calculated.
	[154]	2013	Reduction of 3.3C in ambient temperature has achieved immediately behind the vegetation.
	[74]	2017	The thermal resistance between 0,31m^2K/W to 0,68m^2K/W depending on the VGS.
	[196]	2019	With partial greening, the cooling load could be reduced by 8.8% and heating load by 1.85%.
DSF	[155]	2018	The energy consumption decreases from 7.9% to 14.8%.
	[197] [198]	20162010	Energy saving yields 75% in winter scenario with respect to a single skin facade. Energy saving up to 4% in summer scenario compared to a single skin façade.
	[75]	2016	Heat gains are reduced by 63% with slat angle of 60° compared to the slat angle of 0°.
	[199]	2017	The multi-storey DSF, in average, requires 30% less HVAC related energy demands.
	[200]	2014	5.62% energy reduction in 43 cm depth DSF and 0.46% in 36 cm depth has achieved.
ETFE	[201]	2016	ETFE cushions provide energy saving by 30% and reduction of artificial lighting by 55%.
	[72]	2018	Cavity air temperature is reduced by 7.3–10.5 °C in summer via mechanical ventilation.
	[202]	2018	Annual energy savings of up to 44.9% were predicted for the switchable ETFE foil cushion.
	[203]	2016	A three-layer ETFE system will have an R-Value of approximately 2.9.
Wind wall	[204]	2012	Require 45% less energy to illuminate the interior through daylight-harvesting.
PBR	[205]	2020	This collection reduces energy intensity by nearly 85% (from 86 to 14 KBTU/SF/Year)
	[73]	2019	The U-factor of the algae window profile is between 4.9 W m^{-2} K^{-1} and 53.19 W/m^2 K at different concentrations, with the energy saving up to 20 kWh m^{-2} $year^{-1}$ in South, 8 kWh m^{-2} $year^{-1}$ in East, 14 kWh m^{-2} $year^{-1}$ in West, and energy increase up to 18 kWh m^{-2} $year^{-1}$ in North.
BIPV	[206]	2017	Up to 170% of energy savings was reported in hot-summer and cold-winter zones of China.
	[178]	2016	The BIPV system integrated with PCM can reduce 20–30% cooling energy demand.
	[207]	2017	20–80% net energy saving of adaptive BIPV façade.
BIST	[208]	2012	The fluid is an infrared absorber, which means that 50% of the solar radiation is absorbed from this transparent material.
	[209]	2017	20.2% of cooling load or 64.6% of heating load can be met by the remaining collectors.

(continued on next page)

Table F3 (*continued*)

IF type	Ref	Year	Relevant value
TiO_2	[210]	2010	Titanium has a lower coefficient of expansion and lower thermal conductivity than either steel or aluminum alloys.
Auto-blinds	[79]	2015	Reduce energy consumption in terms of lighting and cooling load requirements up to 50%.
	[201]	2016	Dynamic shades have the potential to save 20–30% in energy use for commercial buildings.
	[201]	2016	The façade of Council House 2 in Melbourne enables saving energy of 82% and reduction of artificial light and mechanical ventilation by 65%.
	[70]	2020	Cooling energy is greatly reduced by 24 kWh/m^2 per year by adding a controlled blind.
Electro-active	[161]	2020	The total energy consumption decreased by 50% for high technology electrochromic panel.
	[211]	2018	A dual-band EC glazing has saving potential between 6 and 30kWh/ft^{2}yr per window area.
	[212]		The reduction of energy consumption in case of use of EC windows is therefore 71%.

Table F4
Energy conversion efficiency for various IF alternatives.

IF type	Ref	Year	Relevant value
ETFE	[188]	2015	For a structure of 1000 m^2 ETFE foil, the hourly energy consumption due to fan operation can be 100 Wh, expected to function 50% of the time, resulting to an approximate energy consumption of 438 kWh per year for the support of the cushion system.
	[78]	2016	One inflation unit can feed a façade ranging from 1400 to 2325 m^2. They are UL-certified and run on a 110 V power, with a power consumption of less than 1 kW.
Wind wall	[213]	2017	The Bahrain World Trade Centre building integrated three 225 kW commercial-scale turbines on bridges spanning the twin towers.
	[214]	2013	A wind wall can produce up to 7% of power needs for building.
	[215]	2015	Experiments in a scale model have shown that efficiencies higher than 40% can be achieved.
	[80]	2017	The wind turbine located inside DSF tunnel at the lower height level was expected to produce the least amount of power output with a value of 487.76 kW h throughout a year.
PBR	[76]	2014	A flat panel PBR with a productivity of 1.9 g/L/day and 40% lipid content, will produce 49,92 kWh/m^2/year.
	[76]	2014	In a vertical tubular PBR, energy usage of pumping the culture is 229 W/m^3 with air pump.
	[76]	2014	A PBR has the potential of producing 12.500 kWh/year with 185 m^2 of surface area.
	[13]	2018	A year after running, the system reached an efficiency of 10% for biogas and 48% for heat.
	[216]	2016	PBR of BIQ house produces 220 kWh/m^2 p.a. of energy as heat energy.
BIPV	[214 60]	20132020	The BIPV have a rated power of 73 kWp in south façade and produce 55.000 kWh/a under the specific local conditions. This covers 30% of the total energy consumption of the building.

Table F4 (*continued*)

IF type	Ref	Year	Relevant value
	[77]	2019	The BIPV system can cover the yearly electricity demand by 120 kWh/façade area/year.
BIST	[217]	2020	For an average fluid temperature of 40 °C, the BIST efficiency is estimated to be approximately 50% at an incoming solar radiation of 600 W/m^2.
	[218]	2014	The maximum efficiency of 35.4% is reported in case of 4 mm glazing thickness as compared to 27.8% in case of 6 mm thickness.
	[209]	2017	75.5% of domestic hot water demand can be met by solar energy in BIST systems.
	[219]	2015	The total collector area of 16 m^2 can get solar gain of 3500kWh/year.
Auto-blind	[79]	2015	The mechanism of the unit is driven by a centrally positioned electric screw-jack linear actuator that operates on very less energy than a regular light bulb.
Electro-active	[220]	2010	The DC voltage needed to change the optical properties of the EC glazing is between 0 and 5 V.
	[120] [221]	20182018	The SPD glazing changes its state from 5% to 55% in the presence of 110 V, 0.07 W AC power. A smectic LC (liquid crystal) glazing achieved "opaque" state for 66 V and 100 Hz (rms) supply whereas 36 V and 1 kHz supplies produce "transparent" state.
	[222]	2016	1 m^2 SPD glazing panel would consume 10.42 kWh of electricity in a year.

Table F5
Annual sequestered carbon by different IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[223]	2015	Annual carbon accumulation of VGS is between 0.99 and 0.14 kg CO_2/m^2.
	[224]	2017	Cochinchinensis has the highest carbon sequestration about 903gCO_2/m^2.
DSF	[155]	2018	The building operational carbon emission is reducing by 14%-17%.
	[225]	2018	The DSF system could potentially reduce the annual operational CO_2eq emission by 9.2%.
	[226]	2015	The 25 years life cycle carbon balance is varying from −51 to −2940 kgCO_2/fu in narrow cavities and + 1673.3 to −2200.2/fu in wide cavities.
ETFE	[12]	2014	2500 m^2 ETFE skin of Media-TIC prevent the release of 114 tCO_2/a into the atmosphere.
PBR	[76] [205]	20152020	To produce 1 ton of algal biomass, 1.8 tons of CO_2 is needed that can be collected with a carbon scrubbing device with carbon capture resin.
	[227]	2019	200 m^2 PBR panels of the BIQ house saves 6/tCO_2/a and additionally 2.5/tCO_2/a is absorbed.
TiO_2	[85]	2017	A road paved with concrete made with the photocatalytic cement can reduce NO_X levels by 20 to 80%, depending on atmospheric conditions.
	[86]	2015	The tile (proSolve370e) coated with TiO_2, counteract the effect of 8750 cars in a day, in the area of 2500 m^2 around the hospital Manuel Gea in Mexico City.
Blind	[79]	2015	Kinetic blinds can save up to 20% of carbon emission for office spaces.
	[228]	2020	Al Bahar tower façade by reducing solar gain and energy consumption can sequestrate CO_2 emissions by 1,750 tones per year.
Electro-active	[229]	2015	CO_2 savings by dynamic EC window is 15.0 kgCO_2/m^2/a in California.
	[230]	2012	EC glass reduces peak load by as much as 35% in new construction and 50% in [30] projects.

Table F6
Recyclability of different IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[101]	2015	The Biotecture system's growing medium can be recycled into brick aggregate. The modules are 100% recyclable into plastic and the backing board can be 100% recycled into backing board. The Jakob system has plants that can be recycled into compost and the stainless steel used can be recycled into stainless steel.
DSF	[231] [102]	20112019	The metals used in DSF systems, particularly the aluminum, are typically recycled into new products. Architectural glass on the other hand is not recycled and most ends up in landfills.
ETFE	[103] [232]	20162010	The ETFE foils and cushions are 100% recyclable.
Wind wall	[233]	2017	Piezoelectric tiles are made from eco-friendly recycled plastic material.
BIPV	[104]	2018	The CIGS, Amorf-Si and Multi-Si BIPV systems have high rate of recyclability as 94.9%, 86.4% and 86.5% respectively.
BIST	[234]	2019	Recycling of ReCiPe BIST system can reduce payback time of 2.66 years.
TiO_2	[105]	2010	TiO_2 can be recycled and reapplied in many photodegradation cycles, maintaining 90% of their activity after 10 cycles of reaction.
Auto-blinds	[235]	2016	Timber-based adaptive shading system used in Melbourne's Council House 2 is recycled.
	[236]	2014	Perforated kinetic is usually made of aluminum, stainless steel, copper, carbon steel and so on which all are recyclable.
	[236]	2017	The wood-based hygromorphic adaptive claddings are recyclable.

Table F7
Reusability of different IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[185]	2014	In the disposal stage, VGS can be reused or landfilled. The steel components can be reused.
ETFE	[237]	2018	The aluminum caps and base profiles of the Texlon® ETFE system can be re-used for new buildings and/or refurbishment projects.

Appendix G. Table G-1 shows some of the IF development challenges and complexities. Table G-2 presents the flexibility value for each IF alternatives, while the ventilation and light performance of different IF alternatives have been detailed in Tables G-3 and G-4. Finally, Table G-5 depicts the key safety features of representative IF alternatives.

Table G1
Fabrication and assembling ease of representative IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[151]	2015	The modular VGS has the easiest assembling and dismantling and maintenance process.
	[238]	2014	It was recognized that green façades are relatively easy to construct.
DSF	[18]		The repair and the replacement of the exterior parts of the DSF are not easy.
	[132 133]	20152011	Air flow in a naturally ventilated DSF is very complex and difficult to analyze due to its unpredictable nature and dynamic conditions.
	[239]	2019	The DSF temperature is depending on the slat angle, cavity thickness, and height.
	[240] [241]	20182017	The analyzing parameters such as window absorptivity, or the position and size, location of the ventilation slots and glass type is complicated process which require professionals.
	[65]	2016	Installation of systems of ventilated façades is simple, but requires qualified workers.
ETFE	[52]	2017	In fact, ETFE structures that are easy to fabricate and fast to erect, they can eliminate the need for scaffolding and large cranes.
	[242]	2016	Thanks to the lightweight membrane the installation process is comparatively effortless. ETFE sheets were delivered to site in rolls which could be lifted with by two men.
Wind Wall	[243]	2010	The design improvements can increase the efficiency of drag force type rotor to about 48%.
	[244]	2016	The building aerodynamic shape, local meteorological data, local building characteristics and location are important parameters that should be considered to enhance wind velocity.
	[245] [237]	20182011	Utilizing wind wall systems requires a thorough understanding of wind characteristics in urban environment and wind energy resources available for harvesting.
PBR	[246]	2016	The wavelength of light used to cultivate algae is a design factor because cultures grow depends on different colors of light.
	[13]	2018	The implementation of PBR requires a blend of experiences that open up a field of interdependence between several disciplines in the field of engineering.
	[73]	2019	The algae concentration, the window size and the combination factor of the algae concentration with the window size, yields the largest effect on the energy consumption.
BIPV	[61]	2017	In the designing process of BIPV system, the lightness, hue of the color and arrangements of modules, shadowing effect, ambient temperature, the direction of the building and the slope of the modules to get higher power output are important factors.
BIST	[134]	2015	The WWR, glazing thickness, water flow velocity and glass properties are the most important factors which requires analyzing by professionals before installing.
TiO_2	[105]	2010	The application was assumed to be done with a roller resulting in no losses during the application; except the 0.15 L of paint that remain in the roller at the end of the day.
	[67]	2020	The following design criteria should be considered: rainfall intensity, wind direction, sun's path and intensity, surrounding neighborhood, building orientation and application levels.
Auto-blinds	[247]	2013	The complexity of modeling and analysis of CABS is increased due to the pre- or post-processing needed to simulate multiple BEMs, selection of the outcomes for each time interval, and compilation of the fragments of simulations into a longer simulation.
Electro-active	[135]	2016	EC technology is not easy, and three hurdles have been identified as follows: a) the coatings need to be nanoporous, b) transparent conductors should have optical transparency, and c) the electrolyte should combine high ion conductivity.

Table G2
Flexibility values for different IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[248]	2016	VGS increases the air quality and flow, also it provides the aesthetic and property value.
	[249]	2014	VGS can reduce long-term noise annoyances and stress-related psychosocial symptoms.
	[66]	2018	A green wall would yield to increase the property unitary and rent value from 6 to 15%.
DSF	[118]	2016	In DSF occupants are able to control their own environment.
	[112]	2011	Aesthetics are often the main aspect for the application of DSF. They give depth and a kind of "crystal image" to the façade.
	[122] [250]	20142015	The main disadvantages of the DSF system as reduction of rentable space, overheating, increased air flow velocity and increased construction weight.
ETFE	[111]	2017	ETFE foil cushions have attractive aesthetic value and transparency properties.
	[52]	2017	ETFE foil cushion creates every building a landmark due to the material characteristics and unique shape.
Wind Wall	[204]	2012	Ned Kahn's Firefly wind wall, celebrates the potential of wind, as clear polycarbonate panels flicker in the wind and trigger the flickering of tiny LED lights at night.
	[113]	2018	VAWT in the high-rise building is very beneficial from the aesthetics point of view, since the wind turbines as foreign objects can affect the visual appearance of the buildings.
	[123]	2012	Usually aerodynamic and mechanical acoustic pollution emitted from wind turbines.
PBR	[246]	2016	Unfortunately, PBRs depend on natural light and are getting inactive by the absence of light.
	[251]	2016	The algae façade is a very visual statement of sustainability in the built environment.
	[205]	2020	The significant issue of PBR, is the possibility of interaction of system with users.
	[205]	2017	Algae technology would need to approach the reliability of static systems.
BIPV	[116]	2020	BIPV can be aesthetically appealing, functional and yet flexible, giving the positive impact on buildings with many opportunities for innovative architectural design.
	[176]	2019	The BIPV modules require an extensive space for an establishment.
	[252]	2019	By increasing solar radiation values, the total efficiency of PV panel is decreasing.
BIST	[253]	2014	The efficiency of BIST collector is not constant; it varies with wind velocity, convective, radiative heat transfer coefficient and solar intensity.
	[114]	2017	BIST can contribute to low-cost installations, which are still aesthetically acceptable.
TiO_2	[57]	2016	This coating can be applied to all types of façade material, frame or structure.
	[254]	2016	Results show that photocatalytic efficiency of TiO_2 remain stable after aging.
	[117]	2012	Titanium is a silver-white metallic element with a low density, good strength, excellent corrosion resistance, very low electrical and thermal conductivity, and is paramagnetic.
	[86]	2018	The Torre de Especialidades façade, is not getting dirty with time, making the whole construction unique in aesthetics also.
Blinds	[255]	2014	In 88% of the cases when the blinds were lowered automatically, people manually raised them within 15 min, indicating a low acceptance of automatic blind adjustments.
	[247]	2013	In some cases, CABS have been praised for providing aesthetically interesting features.

Table G2 (*continued*)

IF type	Ref	Year	Relevant value
Electro-active	[161]	2020	EC glazing requires 20 min for one complete switching cycle (coloring and bleaching).
	[119]	2016	Different colours of Electro-active systems are possible (blue, yellow, green, red, grey, etc.)
	[120] [256]	20182019	Polymer EC glazing is mechanical flexible, multicolor adjustable, short coloring and bleaching switching times, high optical contrast, and high coloration efficient.

Table G3
Ventilation performance by different IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[18]	2014	The wind speed reduction by VGS lowered annual heating costs by 8%, but increased annual cooling costs by 11% and increment about15% for the indoor relative humidity.
	[257]	2017	VGS offer a mechanical ventilation as it reduces the need to extract and filter fresh air.
DSF	[146]	2015	DSF could provide natural ventilation about 60% of the year.
	[142]	2010	The CO_2 concentration evaluation found no significant differences between DSF and SSF.
	[118]	2016	There are three kinds of ventilation in DSF be natural, fan supported or mechanical.
	[258]	2014	DSF provide adequate fresh air at a differential temperature but overheating was noticed during summer.
ETFE	[143]	2017	Computational fluid dynamics (CFD) simulation results show that setting 10–15 elevated ETFE cushions with air outlets will lead to a ventilation rate of about 600,000–800,000 m^3/h.
Wind Wall	[259]	2019	The wind wall of the logan airport parking was designed to provide ventilation and shade.
PBR	[145]	2016	Main advantage of the PBR is the conversion of CO_2 into O_2 during its process that can be utilized to improve the air quality in the building.
BIPV	[144]	2010	BIPV supports the natural ventilation concept of the building.
TiO_2	[53]	2018	The omni-directionality of the quasicrystal geometry of Hospital Manuel Gea TiO_2 façade, is especially suitable to catch winds from all directions.
Auto-blind	[260]	2016	The relative humidity declined with 15% in kinetic façade.
	[261]	2014	During summer, façade panels open to allow ventilation in the cavity in between the external and the internal environment, while during winter panels close for thermal insulation.
	[262]	2018	Doris Sung built a prototype to boost PCM elements in claddings with a self-ventilating ability at comfortable temperatures.
	[228]	2020	The façade of Council House 2 in Melbourne, provides natural ventilation at night by automatically opening the windows and allowing the night air to cool the building.

Table G4
Lighting performance by different IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[130]	2018	Shading effect of VGS lowers daylight illuminance level and increase consumed energy.
DSF	[115]	2020	DSF reduces the natural light transmittance by the second glass skin.
	[124]	2016	Transparency is an important architectural characteristic of DSF systems, providing visual exposure to the surrounding environment of the building, however they can cause glare.
	[263]	2013	All DSF models fail to meet the standard indoor illuminance requirement of at least 200 lx within 75% of the office space.
ETFE	[121]	2017	Offering around 95% light transmission.
	[201]	2011	ETFE-membrane acts as a sunscreen and filters heat and UV-rays by inflating.
	[202]	2018	In comparison to reflective glazing, 64.8% more hours of useful daylight might be achieved.
Wind Wall	[113]	2018	VAWT critically affect the visual appearance of the buildings besides causing shades.
	[264]	2012	Another disadvantage regarding a wind turbine and its impact on the surrounding environment can be expressed with the term "visual impact" or "visual pollution".
PBR	[265]	2016	Average shading co-efficient of 67% has been achieved in PBR. These systems have been endowed with the potential to act as daylight regulators within an architectural framework.
	[76]	2014	Fast growing microalgae can be used as a dynamic sun shading.
	[127]	2017	The direct measurement from 06:22 a.m. till 05:52p.m. has been done in the interior of the simplified model, and the average of the indoor illuminance of 1,049.176 lx was digitally recorded which meets the requirement of illuminance for an office building.
BIPV	[128]	2020	The visible transmittance of BIPV is 23%
	[266]	2013	BIPV could offer manifold advantages of visual comfort effects.
BIST	[267]	2013	The visual transmission of the fluid glass rises by 38% and the solar transmission by 84%.
	[268]	2016	BIST provides control over the thermal load without compromising on transparency.
	[209]	2016	BIST could effectively improve the daylight condition for a single perimeter room by increasing the useful daylight level and reducing the excessive level.
	[114]	2017	BIST can provide visual contact between the interior and the exterior of the building.
Blinds	[269]	2018	Solar blinds are capable to filter direct solar gain to a maximum of 400 W per linear meter.
	[270]	2016	The simulation shows improvement in amount of daylight by 70–150% in dynamic shading.
	[260]	2016	The rotational motion of kinetic blinds, improved daylighting by approximately 50% in summer and spring and about 30% in autumn and winter compared to the base case.
	[126]	2015	The kinetic façade of Council House 2, provide 80% of the occupants with a view.
Electro-active	[212]	2010	EC windows have significant reductions of average annual daylight glare index.
	[125]	2010	EC window is able to modulate the transmittance up to 68% of the total solar spectrum.
	[175]	2018	Solar transmittance of the EC glass sample can be adjusted in the range of 41.6–48.1% when decolored, and up to 6.5% when colored.

Table G5
Safety performance in different IF alternatives.

IF type	Ref	Year	Relevant value
VGS	[271] [272]	20112014	VGS can generate restorative effects leading to decreased stress; improve patient recovery rate and higher resistance to illness in health centers.
	[273]	2017	VGS can produce excess humidity, and possibly promote the growth of microorganisms to which some occupants may be allergic.
	[274]	2019	VGS may have a positive impact on both physical and mental health and wellbeing.
DSF	[275]	2014	For DSF application, high fire-safety requirements need.
	[112]	2011	DSF has a potential advantage of improved security thanks to the two glazed skins.
	[138]	2018	DSF is high risk due to lack of strategies to prevent fire and smoke spread.
ETFE	[121]	2017	ETFE foil membrane has excellent resistance to extreme temperatures.
	[52]	2017	In the case of fire, ETFE could be self-extinguishing due to fluorine in its chemical structure. ETFE produces toxic fumes only when burned at a temperature above 800 °C.
Wind Wall	[276]	2018	Generally modern wind turbines have an extremely good safety record, but there is still the possibility that blade failure can occur in the long operating period of time.
PBR	[205]	2019	Bio-engineers noted that robust regulations and maintenance need to cover health and safety and ensure systems do not fail.
	[137]	2014	PBR can have potential health impacts by leakage or damage that needs to be managed.
BIPV	[277]	2019	The fire test results high risk of BIPV façades due to the possible electrical arcs in string connectors and junction box.
BIST	[278]	2014	As a matter of fact, water in BIST is natural, colorless, odorless, non-toxic and plentiful.
TiO_2	[57]	2016	Self-cleaning features using titanium dioxide (TiO_2) have the most positive impacts on the environment and human health.
	[172]	2013	TiO_2 can decompose harmful organic compounds, kill bacteria and eliminate odors. TiO_2 is a non-toxic chemical base application.
	[279]	2011	Until relevant toxicological and human exposure data, TiO_2 should be used with great care.

Appendix H. The abbreviations used in the text.

Table H1
List of abbreviations and coding.

Abbreviation	Relevant value
ARTS	Alkaline roasting of titania slag
BIPV	Building-integrated photovoltaic
BIST	Building integrated solar thermal
BM	Biomass
DSF	Double skin façade
DSPF	Double-skin perforated façade
EC	Embodied carbon
EE	Embodied energy
ETFE	Ethylene tetrafluoroethylene cushion
GHG	Greenhouse gas
GWP	Global warming potential
HP	Hydro-power
IF	Intelligent façade
LCA	life-cycle assessment
LCC	life cycle costing
MCDM	multi-criteria decision-making
PBR	photo bio-reactor
PCM	Phase change materials

(continued on next page)

Table H1 (*continued*)

Abbreviation	Relevant value
PE	Piezoelectric
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
RS	Renewable system
SLR	Systematic literature reviews
SMA	Shape memory alloys
SPD	Suspended particle device
STCW	Solar thermal curtain wall
VAWT	Vertical axis wind turbines
VGS	Vertical green system
WG	Wind generator
WWR	Window to wall ratio
SEJ	Joules of solar energy
FU	Functional unite
kWp	Kilowatts peak
CU	Currency unit

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Chapter 3.
Preliminary and feasibility study of cases and solution development

Chapter 3 is part of **Phases 2 to 5** of this research thesis (see Fig. 2). This third chapter objective is to limite the boundaries of this doctoral dissertation, defining and analyzing the included case studies. This chapter also aims to define the most appropriate solutions for relevant case studies under this research thesis objectives. The results of this chapter have been collected in **Article B**: *Sustainability Assessment of Household Waste Based Solar Control Devices for Workshops in Primary Schools.* At the end of this chapter there is a complete version of this article B.

3.1. Introduction

At present, the high environmental impact of human activities has some particularly severe drawbacks on the global economy, and by extension, on the livelihood of our entire planet [68]. The characteristics of the construction process of buildings is one of the significant causes of environmental issues. Therefore, this causes have a lasting impact on the well-being of individuals and communities alike, across the world [69]. As a result, governments are preparing policies and laws to fast forward towards more sustainable economies, healthy environments, and favorable societies [70].

Nonetheless, compliance with such policies in some existing edifices constitutes a serious challenge. Especially in buildings that have high levels of occupancy. In the specific case of schools and educational centers, their architectural quality - that comprises the building's infrastructure and the environment in which it sits - is critically important and can either promote health or introduce harmful exposure that can affect children's well-being [71]. Previous research has proven that considering the quality of the educational environment has a direct impact on its students' learning process [72–74]. High-quality educational facilities have an immensely positive impact on pupils' performance, well-being, and conduct. These outstanding facilities lead to an increase of up to 90% in skills and 86% in positive behavioral changes [75]. The Heschong Mahone group [76] highlighted daylight as the main requirement for positive studying environments; with a measured 20% progress in performance in classrooms with the most daylight and biggest windows. Barrett et al. [75] assessed the effects of physical features on 3766 pupils' learning progress in 153 classrooms. This assessment demonstrated that the nature-friendly design principle- comprised of light, sound, temperature, air quality, and closeness to nature - is accountable for 50% of the positive impact on the learning progress.

In recent years, the number of reports documenting the correlation between architectural characteristics and the direct environmental impact has increased [77,78]. In Spain, numerous schools have reported that they could not satisfy the current indoor environmental regulations and requirements for school buildings [79]. For instance, analyses of existing schools in Spain show that many of them do not meet the current sustainability requirements due to their conformity with old mechanisms, guidelines, and criteria [80,81]. These reports show that limitations on the budget and time of the construction processes are two main reasons for the aforementioned challenges.

Following an analysis of these reports, this chapter argues that unsatisfactory thermal and lighting levels are the main challenges for the school buildings. Accordingly, and in order to provide real-scale justifications for these dissatisfactions, a survey on the satisfaction level of lighting and heating in three primary public schools in Spain has been conducted. The results and analysis of the survey to these schools' teachers are listed in Table 3 in Section 3.4.

Previous studies suggest that a possibly good solution could be to rehabilitate these schools. The façade optimization would be the top priority in the rehabilitation process in order to achieve optimum economic, environmental, and social progress [82]. Buildings' skins, as the main components of edifices, contribute greatly to enhancing inhabitants' comfort levels as well as determining a building's energy performance [83].

This chapter explores adding an extra solar-control device as an approach to façade optimization objectives, leading to successfully controlling (a) the amount of light that enters a classroom, and (b) the thermal gains and greenhouse effect.

This chapter also suggests the incorporation of MSW waste items in the development process of the mentioned devices. The addition of such items will contribute to the Op1 (Prevention) and Op2 (Reuse) waste hierarchy of the European waste directive [84]. Op1 is crucial as it reduces waste generation by increasing producer and consumer awareness with initiatives such as workshops and educational activities [85]. Op2's importance lies in it giving a second use to waste and, in consequence, saving it from the waste cycle and reducing the final dumped waste [86].

In this sense, this chapter aims to develop waste-based solar control devices to solve the discussed solar, thermal, and lighting gains considering its overall sustainability dimensions. In order to promote the outcomes of these solar control devices in the waste management hierarchy, the development process has been carried out during workshops with primary schools' students and teachers. By incorporating renewable energy systems in these solar control devices, schools can also raise awareness and promote learning activities related to the advantages of renewable energies.

In this chapter, the process of defining a) feasible solar control device alternatives, b) most sustainable alternatives, and c) workshops, all have been done according to a novel combination set of GMA, MIVES, and Focus group models respectively. The application of the GMA tool generated 96 appropriate alternatives for solar control devices taking into consideration the schools' requirements. The MIVES assessed all alternatives based on 14 sustainability indicators that have been developed by the Focus group. These indicators include: I1) Materials & production cost, I2) Disassembly time & difficulties, I3) CO2 emissions of non- reused components, I4) Percentage of reused materials, I5) Contribution to reduce waste, I6) Color uniformity & specifications, I7) Control of thermal gains, I8) Ventilation contribution, I9) Light control (intensity), I10) Exterior view & glare protection, I11) Color rendering, I12) Flexibility to incorporate children's design, I13) Percentage carried out by children, I14) Real-time feedback to students.

Lastly, MIVES selects the 10 most sustainable alternatives. These alternatives have been presented in Table 4 in Section 3.4. The selected alternatives incorporate waste fill or soil to grow plants inside containers and are very environment-friendly. Regarding social requirements, the selected alternatives met the maximum comfort level of the children, their safety, and their educational needs. Subsequently, the focus group defined the first prototype through workshops with students. being mainly composed of waste, these prototypes have almost zero-cost and zero-emission factors. The applied novel model and its application process have been explained in detail in **Article B** in Section 3.4.

3.2. Contribution to thesis

This chapter contributes to **Phases 2, 3, 4,** and **5** of this research dissertation by defining the project boundaries, case studies, and solutions, as well as proposing assessment and development frameworks for the defined solutions.

The boundaries of this research project have been defined rigorously as external solar control devices that are built using household waste, during educational workshops with primary school students, and are integrated in windows at existing Spanish schools. The defined case studies are three public primary schools - with children aged between 6 and 12 years old - located in three representative municipalities within the greater metropolitan Barcelona area (**Phase 2**). This phase has been carried out alongside experts in both architecture and education: school directors and teachers, educational and energy department members, educational workshops experts, and renewable energy experts, among others. These experts generated an initial questionnaire to analyze the satisfaction level of the teaching team in the included schools regarding their solar control devices (**Phase 2**). The results of this survey showcase teaching teams' dissatisfaction with these devices. The sample schools are representative of a much broader segment consisting of numerous Spanish educational centers with similar circumstances.

This chapter also has three more main contributions. The first is developing a model that combines GMA, MIVES, and Focus groups capable of defining all the feasible alternatives within the boundaries set by this study and assessing the sustainability of these alternatives (**Phase 3**). The second main contribution of this chapter is applying this model in order to find the most sustainable alternative within the guidelines set by this study (**Phase 4**). The third contribution is developing a prototype of the first version of the most sustainable solution for a specific workshop, a specific school building, and its community (**Phase 5**).

By relying on the qualified design process and the comprehensive model, up to 96 alternatives have been defined using GMA and CCA. From these alternatives up to 82 alternatives represent the main types of solar control devices composed of household waste, incorporating energy systems, and able to be assembled during hands-on workshops in primary schools. In this research thesis, it was essential to consider all appropriate alternatives using GMA however difficult it is to define them all. This was due to the novelty of using household waste as a material for workshops to build solar control devices.

The MIVES sustainability assessment was also crucial to find the best alternative in terms of cost, thermal factor, lighting, and colour among other indicators that are studied in depth during **3rd chapter**. MIVES results have been defined as the most sustainable alternative as movable exterior curtains and louvers, built using bottles and other plastic or tetra bricks waste, and integrated with PV panels that are connected to fans. To prove the robustness of these results, a sensitivity analysis has been carried out based on two other scenarios with different requirements weights.

The first prototype and workshop are developed by the Focus group considering all crucial particularities. Figure 3 in Section 3.4 illustrates this prototype and confirms its flexibility to build real mobile louvers using household waste material. Figure 2 in Section 3.4 from workshops confirms that children can build these devices and the process can help increase their awareness of global waste issues. The complete version of this workshop that showcases the latest advances in primary education pedagogy can be found at the following link: https://sites.google.com/view/arqescsost/. Developing the first prototype would also contribute to improving its future versions in terms of times, phases, materials, etc. This first developed prototype has been published as the utility model U201831204 in Spain.

The analyses of prototyped alternatives together with the carried-out workshops highlight that in terms of environmental, technical, and social requirements these alternatives still need to be optimized, as in the next chapters' scope.

3.3. Contribution from the candidate

When the thesis author began his Ph.D. dissertation, his thesis co-directors were already carrying out research activities on the public school environment. The thesis author started participating in these activities, holding their façade refurbishment as a top priority, being a good opportunity for experimental research. In this sense, the candidate took part in sessions with a focus group, moderating and capturing information and reporting them. Such sessions elaborated the process of workshops, defined final alternatives, and developed surveys.

The candidate contributed to the research, proposing state-of-the-art of solar control devices and an extended list of materials, supplements, and structural solutions as well. The candidate also proposed a classification of the various potential household waste items, having into consideration pupils' safety, devices' development time, and their durability. The artwork and diverse materials for workshops were also the responsibility of the candidate.

The candidate looked for the application possibilities of the devices on different sizes of windows and provided a list of possible joints, retracting patterns, and rails. Afterward, the list has been extended by other co-authors. Once all previously mentioned requirements to carry out the workshops have been approved by the focus group, the candidate has contributed to 8 sessions of workshops with schools' children in all 3 schools.

The candidate is the co-author of **Article B**. He took the responsibility for the organization of the paper, main findings, discussion, and conclusion sections. A comprehensive and deep revision of the whole paper has been carried out by the candidate. Finally, the candidate contributed to providing information to publish the utility model of the developed prototype and also to develop a website for the definitive version of the workshops. To sum up, as his thesis co-directors recognize, the candidate had a really important role in this article, which was the first scientific article he participated in.

3.4. Article B

This section presents the published **Article B**. As mentioned, this article covers the 2nd, 3rd, 4th, and 5th phases of this research thesis and includes the followed steps and the results of the sustainability assessments of 96 waste-based solar control devices and their development process during workshops.

sustainability

MDPI

Article

Sustainability Assessment of Household Waste Based Solar Control Devices for Workshops in Primary Schools

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Abstract: Part of the large amounts of waste generated by human activities could have a second use while solving social problems. In this sense, the authors are carrying out a research project involving the participative development of innovative solar control devices integrated into school architecture using household waste. In general, the objectives of this research project are to: (a) optimize pupils' learning process by improving lighting and thermal comfort levels and (b) reduce the generation of Spanish household waste by reusing part of it and increase the teaching community's awareness about this waste. This research article reports on the steps taken to achieve these objectives by characterizing the most sustainable types of the waste-based solar control device. In this sense, this research paper defines and applies a new methodology which combines General Morphology Analysis (GMA), a new tool based on The Integrated Value Model for Sustainable Assessment and Focus groups. First, up to 96 different types of solar control devices composed of household waste have been defined using GMA and, second, these 96 types and conventional roller shutters have been assessed using this new tool. Based on these article results, one of the best alternatives has been prototyped during an initial workshop.

Keywords: household waste; sustainability; general morphology analysis; multi-criteria decision making; MIVES; focus groups; participatory workshops; solar control; primary education

1. Introduction

Global cities waste generation is expected to increase to 2.2 billion tons per year by 2025 [1]. These urban areas create the largest waste share, which is known as municipal solid waste (MSW—Appendix E presents a complete list of abbreviations) [2]. MSW is composed of ordinary daily waste and can be divided up as: (a) "household waste" and (b) waste produced during all the other activities within the city. MSW pollutes the environment, increases toxicity and worsens health [3]. Therefore, most governments and municipalities, among them Spanish entities, are looking for the best waste management mechanisms to deal with MSW [4]. In this sense, the European waste directive defines a waste hierarchy which includes these five options: (Op1) prevention; (Op2) reuse; (Op3) recycling; (Op4) recovery; and (Op5) disposal [5]. Op1 is crucial because it reduces waste generation by increasing producer and consumer's awareness with initiatives such as workshops [6] and educational activities [7]. Op2 is important because it gives a second use to waste and, in consequence, saves it from the waste cycle and reduces the final dumped waste.

In the history of architecture, there are numerous examples of reusing household waste as building components. At the end of the nineteenth century, Antoni Gaudí used broken dishes and bottles for façade cladding [8]. In the early twentieth century several houses were built using glass bottles in North America desert mining towns [9]. From the early 2000s, several walls were constructed using plastic bottles as well [10]. There are also several recent projects on structures composed of plastic bottles [11] and experiences within the Do-it-Yourself social movement [12].

Numerous previous studies and practices about students' learning processes have proven that in school buildings, providing thermal comfort and air quality are crucial [13] as well as natural lighting and visual comfort [14]. The Heschong Mahone group [15] illustrated daylighting and its extension as the main support requirements for studying with 20% progress in classrooms with most daylighting and biggest windows. Barrett et al., [16] by assessing the effects of physical features on 3766 pupils' learning progress in 153 classrooms, demonstrated that Naturalness design principle, comprised by light, sound, temperature, air quality, and links to nature is accountable for 50% of the impact on learning progress, with the other two design principles, Individualization and Simulation, accounting for roughly a quarter each.

Also, it has been reported in numerous Spanish school buildings which could not satisfy the current indoor environmental regulations and requirements for school buildings due to their conformity with obsolete standards, guidelines, and criteria or they are buildings for other purposes converted to schools [17]. These problems have been revealed following the construction of hundreds of schools in limited timeframes and tight budgets because of urgent needs for educational centers in recent years [18] and developed into a serious uncomfortableness issues in June 2017 in hundreds of schools due to extremely hot conditions with abnormally high temperatures in eight Autonomous Communities [19]. This challenge and its effects on students' academic progress became the focus of journalistic reports as a serious social impact during 2017 as shown in Table 1.

Table 1. News articles about the heating problems in 2016 and 2017 in most affected Spanish territories.

Spanish Autonomous Community	Most Read Newspaper		2017 General News	2017 Specific News	2016 General News
	Name	Website			
Andalusia	Ideal	www.ideal.es	21	8	0
Catalonia	La Vanguardia	www.lavanguardia.com	23	2	4
Community of Madrid, Castilla-La Mancha	El País	www.politica.elpais.com	13	1	1
Castile and León	El Norte de Castilla	www.elnortedecastilla.es	5	3	1
Aragon	Heraldo	www.heraldo.es	19	5	3
Extremadura	Región digital	www.regiondigital.com	16	2	1

Legend: Most read newspaper: the most read newspaper in each autonomous community from Spanish National Statistics Institute, available in http://www.ine.es/; 2017 general news: Number of different articles published in June 2017 related to high temperatures problems in general; 2017 specific news: Number of different articles published in June 2017 related to high-temperature problems in school buildings; 2016 general news: Number of different articles published in June 2016 related to high-temperature problems in general.

This problem was caused mainly due to the low performance or non-existence of natural light control devices, with the subsequent inability to properly control these two effects by sun radiation on window panes: (a) the amount of light that enters into a classroom, and (b) the thermal gains due to the greenhouse effect. For example, interior devices control this second effect less successfully. If these devices are properly designed, they can control these two effects, both of which can be desired or undesired [20] depending on the educational requirements. On the other hand, most Spanish schools do not have air conditioning (AC) systems, which could be one of the future solutions for these schools. However, if standard AC equipment were installed, the energy impact of these buildings would increase [21].

By incorporating renewable energy systems in these solar control devices, schools can provide awareness and learning activities related to the advantages of renewable energies [22] which can be explained or observed during workshops for, and usage by, these devices. Reviewing renewable energy systems incorporated in solar control devices, this research project studied 30 existing representative buildings constructed from the late 1990s to present. Most buildings studied have Photovoltaic (PV) systems incorporated in non-movable solar control devices. Few of them are educational buildings such as Voorschoten British School [23].

In this sense, this article is part of a broader project that aims to find the best waste based solar control device to solve the aforementioned abusive solar thermal and lighting gains during workshops with primary students and teachers. In consequence, this device has to be the most sustainable alternative from overall sustainability dimensions including economic, environmental and social issues [24,25]. Therefore, the main objectives of this research paper are: (a) develop a new methodology able to define all the feasible alternatives within the boundaries set by this study and assess the sustainability of these alternatives; (b) apply this methodology in order to find the most sustainable alternative within the guidelines set by this study; and (c) due to satisfaction gained from these first two objectives, develop a prototype the first version of the most sustainable solution for a specific workshop, school building, and its community.

2. Methodology

This research article has developed and applied a new methodology that combines General Morphology Analysis (GMA) [26], a new holistic Multi-Criteria Decision Making (MCDM) tool based on The Integrated Value Model for Sustainable Assessment (MIVES) [27,28] and Focus groups [29] in order to achieve the aforementioned objectives. Before applying this methodology, the boundaries of this specific study have been defined rigorously. This first step was carried out along with experts in architecture and education composed by: school directors and teachers, educational and energy department members, educational workshops experts and renewable energy experts, among others. After defining these boundaries, these experts designed an initial questionnaire for the schools included in the sample and the researchers analyzed their feedbacks.

2.1. GMA to Define Feasible Alternatives

GMA [30] was used to define all the appropriate solar control device alternatives considering the requirements in his specific study. To do so, the researchers first chose the main parameters for the solar control devices and the value range for these parameters; second researchers limited the relevant solution space by examining the internal relationships between parameters using Cross-Consistency Assessment (CCA) and a cross-impact matrix ensuring the consistency and coexistence of each possible pair. This analysis took into account logical contradictions, empirical constraints and normative constraints. Numerous research projects have previously used this method; for example, an application for designing a sustainable school [31]. GMA is a complex methodology which involves analyzing a wide range of organized samples of alternatives and it was chosen precisely in order to be able to take into account all feasible alternatives without missing any interesting options.

2.2. MIVES to Assess the Sustainability of the Feasible Alternatives

MIVES is a MCDM method that incorporates the value function concept in order to define specialized holistic sustainability evaluation tools to obtain global and partial satisfaction indexes [32,33]. Compared to other interesting MCDM for Architecture and Civil Engineering [34] and schools specifically [35], MIVES particular characteristics [27] made it the best method to develop a tool for this case study. To define this tool, the experts followed three phases: (a) determine the basic tree of sustainability requirements for the decision model composed by the most important and discriminative requirements, criteria and indicators for the case study, both quantitative and qualitative; (b) calibrate the value functions that will unify the scales and units of each indicator to a 0 to 1 satisfaction value; (c) assign the weight for each tree requirements component. These experts assigned weights using Analytic Hierarchy Process (AHP) [36] or direct assignation. This second direct method was for cases when the 100% weight had to be assigned between a maximum of 3 components. These workshops and AHP bring objectivity to the requirements tree. Figure 1 presents the sustainability requirements tree with its components and weights ($\lambda_{Ri,k}$).

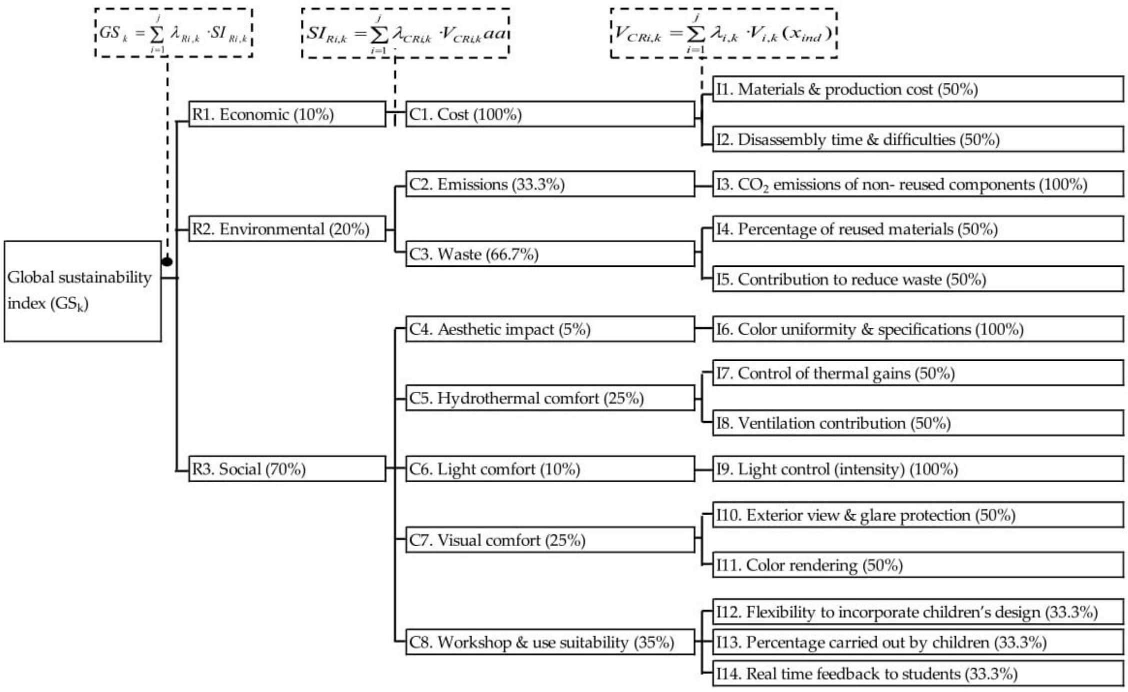

Figure 1. Diagram showing how the Global sustainability index (GS_k) is obtained: adding up the three requirements satisfaction indexes R1 to R3 ($SI_{Ri,k}$), which are obtained by adding up their own criteria C1 to C8 satisfaction indexes ($CI_{Ri,k}$), which are obtained by adding up their own indicator I1 to I14 adimensional aforementioned value functions satisfaction ($V_{i,k}$); all of them corrected considering their own weights.

This project has a high social relevance that explains the particular weights and components of its tree. This is organized in the three main pillars of sustainability as requirements. The economic requirement has one criteria, cost. I1 assesses the materials and construction cost of non-reused components that are mainly joints and renewable energy devices because the reused components supply and assembly during workshops are considered free of cost. The time and difficulties of disassembling operations are considered in I2 because disassembly process will be carried out after finishing the school year and the reuse of connections and renewable energy devices is required. No maintenance costs are considered because solutions will be disassembled when the year is finished because part of these proposed educational objectives will be fulfilled during workshops each year. This requirement does not consider economic gains from the generation of energy because all alternatives will generate low electricity, which will run light-emitting diodes (LED) or fans and provide direct feedback to children's needs as previously explained. This occurs because this project focuses on children's learning and awareness about waste, as explained in detail in the introduction. Nevertheless, the schools will have economic gains from their energy savings and these gains could increase if the schools participate in programs such as Euronet 50/50 [37].

The environmental requirement assesses emissions and waste. Energy consumption of non-reused components has not been considered as an exclusive indicator but covered by I3 CO_2 emissions. This is the case because these components' energy consumption tendency is similar to emissions [18]. In consequence, emissions weights have been assigned considering the importance of both. Energy indicators such as thermal storage and passive systems are not considered because they have low viability in the alternatives and are already assessed in control of thermal gains. I4 assesses the percentage of reused materials in the whole alternative and I5 assesses how important the reuse of the materials chosen is to reduce local and global waste production. Water consumption is unassessed due to its insignificant rate when compared to the water consumed in the Life Cycle Analysis of the building.

The social requirement assesses five important criteria. C4 assesses the color of the solution and its uniformity and fulfilment of architectural specifications. Aesthetic impact does not include architectural specifications or urban & landscape integration because the solution is temporary. C5 assesses the solution capacity to control thermal gains and ventilation contribution taking into account the variability of weather conditions in the sample location. Humidity control has not been included because this has been considered beyond solar protection device requirements. Light comfort in C6 and I9 assesses the capacity of the solution to control the light intensity in lux considering the changing daily and seasonal situations and the changing inside necessities, from light demanding activities to darkness demanding activities. C7 assesses the visual comfort considering in I10 the solution capacity to offer both exterior view and glare protection depending on the requirements, and in I11 the color rendering of objects inside the classroom. C8 assesses the accuracy of the solution during the workshop and its final use. I12 assesses the flexibility to incorporate children's designs and creativity to the final solar control device, and I13 values the percentage of the assembly carried out by children during the complete assembly process. I14 assesses the ability of the device to give real-time feedback to students about the solar control device performance. For example, this occurs if the device produces energy that is consumed by a fan or a LED, which shows how much energy is produced to children in real time. Other social issues have not been assessed because researchers consider that they do not depend on the alternative but the subsequent design, organization and management of the workshop. This is the case of the assembly process of the devices during the workshop. This process will be based on the primary education curriculum [38] in order to increase children's awareness and learning achievements.

These 14 indicators have value functions based on MIVES [32] considered with satisfaction levels from 0 to 1 and depend on five parameters. These parameters determine the function, shape and, in consequence, how each indicator value corresponds to the 0 to 1 satisfaction scale. For example, the Equation (1) to calculate the value function of indicator I1 in this research study has a decreasing concave shape (DCV). Therefore, initial and final value indicator variations will have greater satisfaction scale variations than middle-value indicator variations.

$$V_{I^1} = A + B \cdot \left[1 - e^{-Ki\left(\frac{|Xalt - Xm|}{Ci}\right)^{Pi}} \right] = B \cdot \left[1 - e^{-0.01 \cdot \left(\frac{|X-2200|}{1100}\right)^{1.5}} \right] \quad (1)$$

Equation (1) shows the previously mentioned parameters: $A = 0$ is the response value to $Xmax$; $ki = 0.01$ comes closer to the ordinate of the curve inflection point; $Xalt = X$ is each response to the indicator I1; $Xm = Xmax = 2200$ €/m^2 is the maximum abscissa value considered for I1 in this indicator because it is decreasing, if it were increasing it would be $Xm = Xmin$; $Ci = 1100$ €/m^2 comes closer to the abscissa value of the curve inflection point; 1.5 is the form factor for this concave curve. The parameter B maintains the function within the 0 to 1 range as presented in Equation (2). This equation includes some of the aforementioned parameters and $Xmin = 50$ €/m^2, which is the minimum abscissa value considered for I1.

$$B = \left[1 - e^{-Ki\left(\frac{|Xmax - Xmin|}{Ci}\right)^{Pi}} \right]^{-1} = \left[1 - e^{-0.01 \cdot \left(\frac{|2200-50|}{1100}\right)^{1.5}} \right]^{-1} \quad (2)$$

Indicators I2 to I14 have other parameters that define their value functions shapes: two more DCV, one decreasing linear (DL), seven increasing convex (ICX), and three increasing linear (IL). The researchers have defined these parameters in the course of sessions. Table A8 in Appendix D presents the main parameters and information of each indicator value function with its related references. In these parameters the experts have considered it to be a priority to promote this new implementation and therefore to evaluate positively all small contributions to each alternative. In this sense, maximum and minimum values are respectively 100 and 0 for the assessed indicators using points. In indicators I1 and I3, these values are 10% more or less of the maximum and minimum alternatives values.

The calculation of each indicator has also been designed in collaboration with experts. Table A9 in Appendix D summarizes the main considerations about these calculations.

In the last step of the sustainability assessment tool design, the GS_k for each alternative is defined. As presented in Equation (3), GS_k this is the addition of the partial satisfaction indexes of the three requirements $SI_{Ri,k}$ considering each requirement weight from the previously presented requirement tree (Figure 1).

$$GS_k = \sum_{i=1}^{j} \lambda_{Ri,k} \, . SI_{Ri,k} \quad (3)$$

Similarly, as shown in Figure 1, each of the three $SI_{Ri,k}$ is obtained adding up their own criteria $CI_{Ri,k}$ corrected considering their own weights. Finally, the $CI_{Ri,k}$ is obtained adding up their own indicator's adimensional aforementioned V_{Ik}, considering their own weights from Figure 1. In this present study, this MIVES application also included a sensitive analysis in order to prove the robustness of this new tool.

2.3. Focus Groups to Define a First Prototype and Workshop for a Specific School

Based on the previous steps, one of the most sustainable alternatives was prototyped during a first participatory workshop with students to solve a specific school community problem, representative of this study sample. This alternative selection process, prototype and workshop were also done through Focus groups, which are valuable research tools capable of capturing information that will help to better manage the process of prototype development. This research tool has already been successfully combined with MIVES in previous research projects [39,40]. We also used Focus group as exploratory research in developing new surveys. There are four essential steps in conducting Focus groups: (1) planning (2) recruiting, (3) moderating, and (4) making an analysis and reporting [29]. In this sense, first, we created a purpose statement that reflected what we needed to know from the participant group. The research team drew up several questions on the planned workshops and the best ways to run them, the surveys and designing of the new prototype. When the purpose and desired outcomes had been defined and agreed upon, we identified who should participate in the three sessions, which included teaching team and research project members. One researcher was a moderator who led the group discussion, facilitated interaction among participants and maintained the high-quality interaction that will provide relevant information.

3. Results

3.1. Defining the Problem and Case Study

During this first step, the researchers defined the boundaries of this research project as follows: external solar control devices that are built using household waste during primary educational workshops and are employed for windows in existing Spanish schools. Primary education, also known as elementary, includes grades 1–6 for children from 6 to 12 years old in Spain [41]. These boundaries result from the sample main necessities: (a) external solar control devices; (b) reuse of household waste; and (c) children's awareness about the high generation of waste. Accordingly, the schools studied in this project are all Spanish primary schools. However, in order to be able to carry out a rigorous study with the time and resources available, the researchers defined an initial smaller representative sample. This simplified set public primary school is located in three representative municipalities within the greater metropolitan Barcelona area. Table 2 presents the main characteristics of these municipalities related to this research project [42,43].

Table 2. Main characteristics for the municipalities where the sample schools are located.

	Municipality 1	Municipality 2	Municipality 3
Name	Barcelona	Sant Boi de Llobregat	Torrelles de Llobregat
UTM coordinates ((WGS84) Zone 31T)	E: 429686.70 N: 4582259.10	E: 419270.66 N: 4577599.01	E: 414624.11 N: 4578716.42
Number of inhabitants (inh)	1608,746	82,402	5933
Density (inh/km^2)	15,873.2	3838.0	437.5
Births	13,957	762	58
Deaths	16,003	658	35
Number of public primary schools	169	14	2
Number of schools given questionnaires	30	14	2
Solar irradiation (global horizontal plane) (kWh/m^{2}da & kWh/m^2)	4.7 (1.9–7.6)	4.7 (1.9–7.6)	4.7 (1.9–7.6)
Maximum temperature (June 2016) (°C)	32,5	32	25
Gross domestic product (GDP) per capita (thousands of €)	40.8	21.3	10.4
Registered unemployment	82,597.1	5960.7	299.3

To study this sample, a 10 questions questionnaire was designed in order to evaluate the satisfaction level by schools teaching teams regarding their solar control devices. This questionnaire is included in Appendix A. In the case of Barcelona, only three schools per district were given this questionnaire. Table 3 presents the results of these questionnaires that were considered in this research project to define the schools in the sample needs on solar control devices. As shown in this table, the most commonly used solar control device in the schools included in the sample at present are exterior roller shutters, which have been complemented with other solar control devices in order to improve school lighting and thermal comfort in almost all school centers.

Table 3. Results of questionnaires from schools which submitted answers related to solar control devices.

		Municipality 1	Municipalities 2 and 3	Standard Deviation
Existing kind of solar control system (question 3)	Exterior roller shutter	59%	50%	0.06
	Percentage of roller shutters that have been complemented	88%	100%	0.08
Lighting performance satisfaction for solar control devices (question 4)	High satisfaction	34%	62%	0.20
	Average satisfaction	24%	19%	0.04
	Low satisfaction	42%	19%	0.16
Thermal performance satisfaction for solar control devices (question 5)	High satisfaction	14%	31%	0.12
	Average satisfaction	24%	31%	0.05
	Low satisfaction	62%	38%	0.17
Solar control devices (question 7)	work properly as new	31%	50%	0.13
	need minimum maintenance	48%	38%	0.08
	need important repair	7%	6%	0.00
	need replacement	14%	6%	0.05

3.2. Determining the Appropriate Alternatives

This second step defined the most important parameters for this case study and assigned relevant values for each parameter following the aforementioned GMA. Table A3 presents the eight main parameters and their relevant values.

These parameters do not generate specific solutions but types of solutions, which reduce the amount of generated alternatives and, therefore, simplify the whole process. For the first parameter about the position, two values include devices installed on the ground floor and other levels of the façade. Devices installed in the playground as isolated elements were outside the scope of this study and therefore discarded. The second parameter is mobility and includes two opposite values, either the device is fixed and immovable or moveable being foldable, retractable, or scrollable. The third parameter is the types of solar control devices and considers three relevant values according to the stated boundaries.

In consequence, interior devices are discarded. This study focuses on devices that students can control either manually or with up-down commands whereas fully automated devices are discarded. Venetian blinds, roller blinds, extensible awning, solar control glass, glass vinyl, transparent or opaque building integrated photovoltaic elements and building integrated solar thermal systems [20] have been discarded since they have been considered unable to be composed of household waste.

The fourth parameter is the type of household waste exposed to weathering [44], and four types are defined: (4.1) Bottles, either polyethylene terephthalate or high-density polyethylene previously used for food and drinking products; (4.2) Other containers, e.g., tetra briks, yogurt recipients, plastic cups …; (4.3) opaque or translucent superficial elements, such as opened tetra briks, polystyrene and polyethylene plates, dishes, egg containers covers …; and (4.4) Small elements such as bottle covers. On the other hand, the following materials have been discarded: (a) waste containers whose shape and material properties could cause injuries, such as metals, glass, home appliances …; (b) waste that may have been in contact with toxic products and allergens such as cleaning products and paints; and (c) low durability products such as plastic bags, paper and paperboard that cannot last exposed to exterior weathering during one school term. The fifth parameter is the filling material and has two operational values: waste such as expanded polystyrene, paper, paperboard, plastic bags and soil to grow plants. Water as filling material has also been discarded to avoid problems related to stagnant water such as algae, mosquitoes … [45].

The last three parameters are elements which are not waste but produced and bought for the device manufacture and application. The sixth parameter is the type of auxiliary material and has five relevant values. The seventh parameter is the type of renewable energy system and has two possible values: (7.1) rigid small photovoltaic (PV) panels and (7.2) Piezoelectric elements. This project discards the following systems: (a) biomass, hydro, geothermal and marine technologies because they are not suitable for the case study [46]; (b) solar thermal because of their inadequate pipe temperatures and pressures for children; (c) adsorption systems because they are too complex; and d) non-rigid flexible or amorphous PV elements [47], because waste alternatives are made of limited pieces and lack amorphous surfaces. The last parameter is the type of device that consumes the energy generated by the renewable system and has two values: (8.1) a fan that optimizes ventilation and (8.2) light-emitting diodes (LED). The following have been discarded: (a) connection to the electric network or batteries because of the low amount of energy generated and (b) connection to a system to pump water upwards and then generate energy via hydropower because of its complexity and inconveniences of water running circuits prone to sanitary and durability issues [45].

In the course of these sessions, experts have used GMA and CCA to reduce the amount of possible solar control alternatives which were developed by these parameters and their possible values to a subset that has primary internal consistency. The internal relationships among these eight parameters have been studied by an analysis-synthesis process. These parameters were compared with one another by means of a cross-impact matrix which took into account the boundaries of the project and the consequent inconsistencies, which are classified and presented in Table A4 in Appendix C. As shown there were logical and empirical constraints but no normative constraints.

From this GMA resulted in the 82 feasible alternatives incorporated in Tables A1 and A2 in Appendix B, one table for each value of parameter 1. At this point, the researchers studied cross-impact matrixes without particular configurations or subsets (Table A5) in order to find 14 more alternatives that were non-logical and unexpected, which are presented in Tables A6 and A7 in Appendix C. To do so, several values were added although they were incompatible with the stated boundaries. These added values for parameter 3 are "3.4. Solid panels", "3.5. Solar control glass" and "3.6. Roller shutters" and for parameter 4 are "4.5 cardboard" and "4.6 plastic bags". Consequently, from these final total 96 alternatives, the 14 non-logical options helped the researchers to contrast and confirm the 82 logical alternatives, as explained in the discussion section.

3.3. Results for Sustainability Assessments of Alternatives

This part determines the sustainability of the aforementioned 96 alternatives as well as the sustainability of exterior roller shutters, which are the most commonly used solar control device of the sample as previously shown in Table 3. These roller shutters are devices beyond these new sustainability assessment tool boundaries. Nevertheless, they have been assessed to have more quantitative information when comparing them to the experimental prototypes.

The main results of this sustainability assessment are the global sustainability index for each alternative GS_k and the three partial satisfaction indexes of the economic, environmental, and social requirements $SI_{R1,k}$, $SI_{R2,k}$, and $SI_{R3,k}$, respectively.

Table A10 in Appendix D presents all these indexes for all the 97 assessed devices. Table 4 illustrates the ten alternatives that have maximum partial satisfaction indexes and maximum global sustainability indexes.

Table 4. Sensitivity analysis comparing two other weight scenarios of the solar control device alternative types.

Sustainability Requirement	Research Project Scenario (E1)	Neutral Scenario (E2)	Economically Biased Scenario (E3)	Variation from Scenario E1 to E2	Variation from Scenario E1 to E3
Economic	10%	33.33%	50%		
Environmental	20%	33.33%	30%		
Social	70%	33.33%	20%		
	GS_k	GS_k	GS_k		
Alternative 1	0.81	0.81	0.82	0%	−1%
Alternative 24	0.82	0.78	0.78	4%	4%
Alternative 25	0.82	0.78	0.78	4%	4%
Alternative 26	0.82	0.81	0.80	1%	2%
Alternative 28	0.82	0.79	0.75	3%	7%
Alternative 42	0.81	0.80	0.81	1%	0%
Alternative 65	0.82	0.77	0.76	5%	6%
Alternative 66	0.82	0.77	0.77	5%	5%
Alternative 67	0.80	0.78	0.75	2%	5%
Alternative 69	0.80	0.73	0.67	7%	13%
			Average	3%	5%

In general, the results showed that the most sustainable alternatives with maximum global index are movable exterior curtains and louvres built using bottles and other plastic or tetra briks waste, respectively, and integrated with PV panels which are connected to fans.

3.4. First Prototype of One of the Most Sustainable Alternative for a Specific Case Study

The first prototype was defined taking into account their future installation in a specific school included in the sample. This educational center was chosen from the 46 interviewed centers of the 185 sample schools, presented in Table 2. This center was chosen because it had both the gravest lack of solar controls and a teaching team more prone to collaborate in this project, which had been proven to be crucial for participative projects in schools [48]. The main characteristics of this school [49] are representative of an important part of schools included in this sample study. This first design and prototype was 0.6 × 1.95 m and solved part of one window solar control, although it aims to solve the solar control issues on the 33 classrooms windows on the same building façade in the future. These windows have these traits in common: south-east orientation, 1.95 m high, 2.40 m wide, have no shading from nearby buildings, have curtains as control devices. Following these characteristics, the aforementioned Focus groups chose alternative 24, which is ground floor louvres, that are movable, use superficial waste, incorporate PV and a fan. The main reasons for choosing this alternative is that it had the best social criteria sustainability index and, therefore, was more flexible to incorporate children's design & creativity. Children could carry out a higher percentage of its installation and had better real-time feedback to students for its performance. Among the different possibilities within this alternative, vertical louvres were chosen according both to the orientation and this school's teaching team preferences. Finally, tetra briks were chosen because this school had an extra amount of tetra briks available as part of a European Union program that was providing milk to the school [49].

4. Discussion

This section discusses the previous results about this project sample, the 96 new solar control devices alternatives plus the current roller shutters and the first design and prototype for the most sustainable device.

In Section 3, the analysis of the sample proves teaching teams' dissatisfaction regarding their schools solar control devices. The sample schools are representative of a much broader sample consisting of numerous Spanish educational centers with similar circumstances. Consequently, the researchers expect that a huge number of primary education teams in Spain have low satisfaction levels for their current solar control devices, regarding thermal and lighting performance and their workability.

Up to 96 alternatives have been defined using GMA and CCA, which are listed in Appendix B. Up to 82 alternatives represent the main types of solar control devices composed of household waste, incorporating energy systems, and able to be assembled during participatory workshops in primary schools. This representability has been ensured by relying on the qualified design process applying the comprehensive methodologies incorporating sessions with multidisciplinary experts. The rest are 14 non-logical alternatives beyond some of these research limits have also been generated to prove it. All alternatives are types of solar control devices and, therefore, each one includes numerous possible specific solutions that will be studied in the future steps of this research project. This simplification gives flexibility to the results, as has already been explained in the methodology.

The 96 alternatives and the roller shutters sustainability assessment results are shown in Appendix D. The ten most sustainable alternatives, their three requirements satisfaction ($SI_{Ri,k}$) and their Global Index (GS_k) are presented in Table 3. These best alternative types are exterior louvres and curtains. They differ because exterior louvres have the best social indexes while exterior curtains have the best environmental indexes. These most environmentally friendly alternatives incorporate waste fill or soil to grow plants inside containers. Regarding social requirements, which are the most important for this research project, the best solutions incorporate PV and fans. On the other hand, the 14 non-logical alternatives had the lowest global sustainability indexes and the lowest environmental and social indexes, which are the most crucial indicators for this project as previously explained. This confirms that GMA has properly defined the appropriate alternatives for this project. On the other hand, roller shutters are out of the scope for this research project and, therefore, their low sustainability index was expected, mainly because it is not possible to use them for workshops, since they give no feedback to students, do not allow children's design and their hydrothermal and light control behavior should improve for educational purposes as presented in Section 3.1. To prove the robustness of these results, a sensitivity analysis has been carried out considering two other scenarios with different requirements weights as shown in Table 3. The two other considered scenarios are if decision makers' had either a neutral or an economically biased point of view. The neutral scenario gives the same third part weight to each requirement. The Economic scenario gives 50% of the weight to the economic requirement, 30% to the environmental and 20% to the social. As seen in Table 3, the variation for most alternatives is very low, with the maximum variation occurring in alternatives 11 and 84, because they are the worst from the environmental and social points of view.

Defining and carrying out the first prototype and workshop as shown in Figure 2 [49] has been useful to: (a) confirm it is possible to build real mobile louvres mainly based on household waste material as Table 4 and Figure 3 present; (b) confirm children can build them; (c) confirm children can be more aware of global waste problem and of solar control devices from this workshop; and (d) detect the strengths and weaknesses encountered in this first workshop in order to improve future versions in terms of contents, times, phases, materials, etc.

Figure 2. Children developing waste-based solar control devices during the first workshop.

Figure 3. First waste-based solar control devices prototype developed during the first workshop.

5. Conclusions

Compared to the previous similar projects presented in the introduction, this research project main novelties are: (a) the definition of a new methodology that combines GMA, MIVES, and Focus groups for the first time and (b) the application of this methodology in order to find the most sustainable alternative among all feasible possible waste based solar control devices for primary workshops about sustainable architecture.

In consequence, this project has satisfied its objectives because it has: found all the appropriate waste based solar control devices alternatives to be built in primary workshops; assessed the sustainability of these alternatives to determine the most sustainable devices; and has built the first new solar control devices prototypes during a first workshop. It has also contributed to environmental awareness, particularly in the 46 schools interviewed and the schools where the first prototype and workshop has been developed.

The proposed solutions are composed of household waste compatible with primary children's safety, incorporate energy systems and solve the sample schools' serious lack of solar control. Therefore, they contribute to provide maximum comfort level and energy efficiency in these schools. Furthermore, being mainly composed of waste, they have almost zero-cost and zero-emission factors.

These project methodologies have once more proven very useful to carry out research because of: (a) GMA efficiency to identify the appropriate alternatives; (b) MIVES versatility to generate agile MCDM tools for specific problems; and (c) Focus group capacity to consider all crucial particularities. In this research project, it was essential to be able to consider all appropriate alternatives using GMA and it was difficult to define them all because of the novelty of using household waste as a material for workshops to build solar control devices. The MIVES sustainability assessment was also crucial in order to find the best alternative in terms of cost, thermal, light and color performance among others indicators that have been studied in depth.

In this sense, the next steps in this research project will assess in depth these aspects of this device: its thermal and lighting performance, its components mechanical and durability performance and its overall sustainability benefits. In the future, this project will also define a definitive version of its workshop based on the latest advances in primary education pedagogy.

As recommendations for future studies, this project considers these methodologies applicable to similar challenges after adapting them to each case and encourages researchers to do so by relying on this present study. For example, they can be used to define and assess waste based solar protections for playgrounds or high schools. In this sense, both this and other similar projects are expected to promote awareness and better management of our Society critical waste generation.

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Appendix A

First questionnaire

(1) What's the name of your school center?
(2) In which municipality is located your school?
(3) What kind of solar control device does your school building have?
   a. Exterior roller shutter
   b. Not movable Louvre blinds
   c. Exterior shutters
   d. Exterior textile blinds
   e. Exterior non-movable awning
   f. Exterior roller awning
   g. Balconies and cantilevers
   h. Pergola Shelter in the playground close to openings
   i. Awnings in the playground close to openings
   j. Vegetation and trees
   k. Textile interior curtains
   l. Dark window glazing
   m. Special window glazing with drawings
   n. Louvre blinds with Photovoltaic panels incorporated
   o. Other
   p. None
(4) Do you consider that these devices are flexible enough considering the entrance of sunlight in order to do the different learning activities you do?
   a. Yes, always
   b. Yes, in 75% of the cases

   c. Yes, in 50% of the cases
   d. Yes, in 25% of the cases
   e. No, never.
(5) Do you consider that these devices are able to sufficiently control the entrance of sunlight in order to achieve thermal comfort of school interior spaces?
   a. Yes, always
   b. Yes, in 75% of the cases
   c. Yes, in 50% of the cases
   d. Yes, in 25% of the cases
   e. No, never.
(6) How long ago were these devices assembled?
   a. 0–2 years
   b. 3–5 years
   c. 6–10 years
   d. 11–25 years
   e. More than 25 years
(7) Are these devices working properly?
   a. Yes, they are new
   b. They need minimum maintenance work, such as paining, varnishing ...
   c. They need an important rehabilitation as they are broken in several parts.
   d. They should be replaced for new devices since they don't work and/or are all broken.
(8) Which of the schools you know have the best solar protection to control light and temperature for spaces in those centers?
(9) Which of the schools you know have the worst solar protection to control light and temperature for spaces in those centers?
(10) Would you be willing to do a workshop with children and teachers to build solar protections with household waste during the next year and a half?
   a. Yes
   b. I would like to know more about this research project before deciding
   c. No

Appendix B

Table A1. Alternative solar protection devices for ground floor installation (1.1).

Mobility	Control	Waste	Filling	Connectors	System	Use	N°
2.1. Fixed	3.1. Louvre blinds	4.3. Superficial	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	1
						8.2. LED	2
					7.2. Wind	8.2. LED	3
	3.2. Exterior curtains	4.1. Plastic Bottles	5.1. Waste + 5.2. Soil	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	4
						8.2. LED	5
					7.2. Wind	8.2. LED	6
		4.2. Other containers	5.1. Waste + 5.2. Soil	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	7
						8.2. LED	8
					7.2. Wind	8.2. LED	9
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	10
						8.2. LED	11
					7.2. Wind	8.2. LED	12
		4.4. Small	5.2. Soil	6.1 + 6.3	7.1. PV	8.1. Fan	13
						8.2. LED	14

					7.2. Wind	8.2. LED	15
	3.3. Sun sail & awnings	4.1. Plastic Bottles	5.1. Waste	6.1 + 6.2	7.1. PV	8.1. Fan	16
						8.2. LED	17
		4.2. Other containers	5.1. Waste	6.1 + 6.2	7.1. PV	8.1. Fan	18
						8.2. LED	19
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	20
						8.2. LED	21
		4.4. Small	N/A	6.1 + 6.3	7.1. PV	8.1. Fan	22
						8.2. LED	23
2.2. Movable	3.1. Louvres	4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	24
						8.2. LED	25
	3.2. Exterior curtains	4.1. Plastic Bottles	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	26
						8.2. LED	27
		4.2. Other containers	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	28
						8.2. LED	29
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	30
						8.2. LED	31
		4.4. Small	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	32
						8.2. LED	33
	3.3. Sun sail	4.1. Plastic Bottles	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	34
						8.2. LED	35
		4.2. Other containers	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	36
						8.2. LED	37
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	38
						8.2. LED	39
		4.4. Small	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	40
						8.2. LED	41

Table A2. Alternative solar protection devices for installation in levels from first floor on (1.2).

Mobility	Control	Waste	Filling	Connectors	System	Use	N°
2.1. Fixed	3.1. Louvre blinds	4.3. Superficial	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	42
						8.2. LED	43
					7.2. Wind	8.2. LED	44
	3.2. Exterior curtains	4.1. Plastic Bottles	5.1. Waste	6.1 + 6.2	7.1. PV	8.1. Fan	45
						8.2. LED	46
					7.2. Wind	8.2. LED	47
		4.2. Other containers	5.1. Waste	6.1 + 6.2	7.1. PV	8.1. Fan	48
						8.2. LED	49
					7.2. Wind	8.2. LED	50
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	51
						8.2. LED	52
					7.2. Wind	8.2. LED	53
		4.4. Small	N/A	6.1 + 6.3	7.1. PV	8.1. Fan	54
						8.2. LED	55
					7.2. Wind	8.2. LED	56
	3.3. Sun sail & awnings	4.1. Plastic Bottles	5.1. Waste	6.1 + 6.2	7.1. PV	8.1. Fan	57
						8.2. LED	58
		4.2. Other containers	5.1. Waste	6.1 + 6.2	7.1. PV	8.1. Fan	59
						8.2. LED	60
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	61
						8.2. LED	62
		4.4. Small	N/A	6.1 + 6.3	7.1. PV	8.1. Fan	63

						8.2. LED	64
2.2. Movable	3.1. Louvres	4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	65
						8.2. LED	66
	3.2. Exterior curtains	4.1. Plastic Bottles	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	67
						8.2. LED	68
		4.2. Other containers	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	69
						8.2. LED	70
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	71
						8.2. LED	72
		4.4. Small	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	73
						8.2. LED	74
	3.3. Sun sail	4.1. Plastic Bottles	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	75
						8.2. LED	76
		4.2. Other containers	5.1. Waste	6.1 + 6.2 + 6.5	7.1. PV	8.1. Fan	77
						8.2. LED	78
		4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	79
						8.2. LED	80
		4.4. Small	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.1. Fan	81
						8.2. LED	82

Appendix C

Table A3. Main parameters for this study case and their relevant values.

Parameter	Relevant Values
1. Position of the solar control device in the façade	1.1. Ground floor 1.2. First floor
2. Mobility of the solar control device	2.1. Fixed 2.2. Movable
3. Types of solar control devices	3.1. Louvre blinds 3.2. Exterior curtains 3.3. Sun sails & awnings
4. Type of domestic reused waste exposed to weathering	4.1. Plastic Bottles 4.2. Other containers 4.3. Superficial elements 4.4. Small elements
5. Type of materials filling containers and bottles	5.1. Filling waste 5.2. Soil with plants
6. Types of auxiliary materials	6.1. Plastic or metallic connections 6.2. Plastic or metallic profiles 6.3. Nylon or cloth twines 6.4. Adhesive 6.5. Mobile system
7. Types of renewable energy systems	7.1. PV panels 7.2. Piezoelectric elements
8. Types of devices that use the energy produced	8.1. Fan 8.2. LEDS

Table A4. Inconsistencies considered in the GMA and CCA.

Type of Inconsistency	Relevant Values
1. Logical contradictions	Value 3.1 only made with 4.3 because louvre elements are superficial. Values 5.1 and 5.2 only for values 4.1 and 4.2 because filling needs a recipient to be filled. Value 6.5 only logical with value 2.2.
2. Empirical constraints	Value 5.2 only for 1.1 because in the ground floor the problems from leaking plants will be less. Value 8.1 only with 7.1 because 7.2 will involve ventilation for itself. Value 2.2 incompatible with 5.1 and 7.2 because resulting alternatives high complexity. Value 3.3 incompatible with 7.2 because the horizontal position limits its viability.
3. Normative constraints	None

To obtain unexpected alternatives, matrixes without particular configurations were prepared such as:

Table A5. Unexpected solar control devices alternatives types.

	4.3. Superficial	4.5. Cardboard	4.6. Plastic Bags
3.1. Louvre blinds			
3.2. Exterior curtains			
3.3. Sun sails & awnings			
3.4. Solid panels	UA		
3.5. Solar control glass			UA
3.6. Roller shutters	UA	UA	

Legend: UA-Unexpected Alternative.

From this matrix the following alternatives have been added:

Table A6. Added alternatives 83 to 89 for ground floor solar protective devices (1.1).

Mobility	Control	Waste	Filling	Connectors	System	Use	N°
2.1. Fixed	3.4. Solid panels	4.5. Cardboard	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	83
						8.2. LED	84
	3.5. Solar control glass	4.3. Superficial	N/A	6.4	N/A	N/A	85
		4.6. Plastic bags	N/A	6.4	N/A	N/A	86
2.2. Movable	3.6. Roller shutters	4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.2. LED	87
	3.4. Solid panels	4.5. Cardboard	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.2. Fan	88
						8.2. LED	89

Table A7. Added alternatives 90 to 96 for solar protective devices in levels from first floor on (1.2).

Mobility	Control	Waste	Filling	Connectors	System	Use	N°
2.1. Fixed	3.4. Solid panels	4.5. Cardboard	N/A	6.1 + 6.2 + 6.3	7.1. PV	8.1. Fan	90
						8.2. LED	91
	3.5. Solar control glass	4.3. Superficial	N/A	6.4	N/A	N/A	92
		4.6. Plastic bags	N/A	6.4	N/A	N/A	93
2.2. Movable	3.6. Roller shutters	4.3. Superficial	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.2. LED	94
	3.4. Solid panels	4.5. Cardboard	N/A	6.1 + 6.2 + 6.3 + 6.5	7.1. PV	8.2. Fan	95
						8.2. LED	96

Appendix D

Table A8. Main parameters and information for each indicator (Ix) value function.

I_x	Unit	$X_{max.}$	$X_{min.}$	Ci	Ki	Pi	Shape	References
I1	(€/m²)	2200	50	1100	0.01	1.5	DCV	[50,51]
I2	(points)	100	0	50	0.01	1.5	DCV	[11]
I3	($kgCO_2/m^2$)	600	10	300	0.01	1	DL	[51]
I4	(points)	100	0	50	0.01	0.5	ICX	[6,52]
I5	(points)	100	0	50	0.01	1	IL	[53]
I6	(points)	100	0	50	0.01	0.5	ICX	[20]
I7	(points)	100	0	50	0.01	0.5	ICX	
I8	(points)	100	0	50	0.01	1	IL	
I9	(points)	100	0	50	0.01	0.5	ICX	
I10	(points)	100	0	50	0.01	1	IL	
I11	(points)	100	0	50	0.01	0.5	DCV	
I12	(points)	100	0	50	0.01	0.5	ICX	[54]
I13	(points)	100	0	50	0.01	0.5	ICX	[6,52]
I14	(points)	100	0	50	0.01	0.5	ICX	

Legend: DCV—Decreasing Concave; DL—Decreasing Lineal; ICX—Increasing Convex; IL—Increasing Lineal.

Table A9. Main considerations for the calculations corresponding to each indicator.

Ix	Considerations for These Calculations
I1	Cost of: (a) connection composed of metallic screws, washers, knots, plastic connections, twines, adhesives, (b) substructure with metallic frames, plastic posts…, (c) mobile system, (d) energy system and (e) LED or fan.
I2	The disassembling operations for connections among solar control device parts, energy system and the connected devices.
I3	Emissions from the components described in I1.
I4	The surface of the components described in I1 and household waste elements.
I5	The recyclability rate of the waste used in each solar control device.
I6	The color uniformity of the household waste used in each alternative solar control device.
I7	The thermal behavior of each solar control device.
I8	The ventilation behavior of each solar control device and the incorporation of a fan.
I9	The light control behavior of each solar control device.
I10	The transparency of each solar control device.
I11	The rendering of the household waste, based on each solar control device.
I12	Flexibility to incorporate children's design & creativity depending on the type and size of household waste, whether this waste is paintable and if there is soil for growing plants.
I13	The contribution rate of children's assembly process considering the operation—screw, paint, glue, tie, cut or plant–, the number of operations depending on the type and size of waste and the percentage of children operations as part of the total assembly operations.
I14	Children's feedback regarding use of LED, fan or plants.

Table A10. Sustainability indexes.

	Alternatives in Ground Floor Solar Protection Devices (1.1) Fixed (2.1)	$SI_{R1,k}$	$SI_{R2,k}$	$SI_{R3,k}$	GS_k
1	Ground floor, fixed, louvres, superficial, PV, fan	0.89	0.72	0.82	0.81
2	Ground floor, fixed, louvres, superficial, PV, LED	0.89	0.72	0.78	0.78
3	Ground floor, fixed, louvres, superficial, WIND, LED	0.72	0.72	0.78	0.76
4	Ground floor, fixed, exterior curtains, bottles, waste + soil, PV, fan	0.88	0.85	0.75	0.79
5	Ground floor, fixed, exterior curtains, bottles, waste + soil, PV, LED	0.89	0.85	0.71	0.76
6	Ground floor, fixed, exterior curtains, bottles, waste + soil, wind, LED	0.72	0.85	0.71	0.74
7	Ground floor, fixed, exterior curtains, other containers, waste + soil, PV, fan	0.75	0.93	0.71	0.76
8	Ground floor, fixed, exterior curtains, other containers, waste + soil, PV, LED	0.76	0.93	0.67	0.73
9	Ground floor, fixed, exterior curtains, other containers, waste + soil, wind, LED	0.59	0.93	0.67	0.71
10	Ground floor, fixed, exterior curtains, superficial, PV, fan	0.94	0.67	0.68	0.70
11	Ground floor, fixed, exterior curtains, superficial, PV, LED	0.95	0.67	0.64	0.68
12	Ground floor, fixed, exterior curtains, superficial, LED	0.78	0.67	0.64	0.66
13	Ground floor, fixed, exterior curtains, small, PV, fan	0.67	0.67	0.73	0.71
14	Ground floor, fixed, exterior curtains, small, PV, LED	0.67	0.67	0.69	0.68
15	Ground floor, fixed, exterior curtains, small, wind, LED	0.51	0.67	0.69	0.66
16	Ground floor, fixed, sun sail, bottle, waste, PV, fan	0.68	0.80	0.74	0.75
17	Ground floor, fixed, sun sail, bottle, waste, PV, LED	0.68	0.80	0.70	0.72
18	Ground floor, fixed, sun sail, other containers, waste, PV, fan	0.52	0.84	0.74	0.74
19	Ground floor, fixed, sun sail, other containers, waste, PV, LED	0.53	0.84	0.70	0.71
20	Ground floor, fixed, sun sail, superficial, PV, fan	0.86	0.64	0.67	0.68
21	Ground floor, fixed, sun sail, superficial, PV, LED	0.87	0.64	0.63	0.65
22	Ground floor, fixed, sun sail, small, PV, fan	0.37	0.55	0.73	0.65
23	Ground floor, fixed, sun sail, small, PV, LED	0.37	0.55	0.68	0.63
	Alternatives in the Ground Floor (1.1) that Move (2.2)	$SI_{R1,k}$	$SI_{R2,k}$	$SI_{R3,k}$	GS_k
24	Ground floor, movable, louvres, superficial, PV, fan	0.79	0.70	0.86	0.82
25	Ground floor, movable, louvres, superficial, PV, LED	0.79	0.70	0.86	0.82
26	Ground floor, movable, exterior curtains, bottle, waste, PV, fan	0.78	0.83	0.82	0.82
27	Ground floor, movable, exterior curtains, bottle, waste, PV, LED	0.78	0.83	0.78	0.79
28	Ground floor, movable, exterior curtains, other containers, waste, PV, fan	0.64	0.90	0.82	0.82
29	Ground floor, movable, exterior curtains, other containers, waste, PV, LED	0.64	0.91	0.77	0.79
30	Ground floor, movable, exterior curtains, superficial, PV, fan	0.84	0.65	0.75	0.74
31	Ground floor, movable exterior curtains, superficial, PV, LED	0.84	0.65	0.71	0.71
32	Ground floor, movable, exterior curtains, small, PV, fan	0.56	0.65	0.80	0.75
33	Ground floor, movable, exterior curtains, 17mall, PV, LED	0.56	0.65	0.76	0.72
34	Ground floor, movable, sun sail, bottle, waste, PV, fan	0.62	0.79	0.77	0.76
35	Ground floor, movable, sun sail, bottle, waste, PV, LED	0.62	0.79	0.73	0.73
36	Ground floor, movable, sun sail, other containers, waste, PV, fan	0.47	0.83	0.77	0.75
37	Ground floor, movable, sun sail, other containers, waste, PV, LED	0.47	0.83	0.73	0.72
38	Ground floor, movable, sun sail, superficial, PV, fan	0.78	0.63	0.70	0.69

39	Ground floor, movable, sun sail, superficial, PV, LED	0.78	0.63	0.66	0.66
40	Ground floor, movable, sun sail, small, PV, fan	0.32	0.54	0.76	0.67
41	Ground floor, movable, sun sail, small, PV, LED	0.32	0.54	0.72	0.64
	Alternatives from the First Floor on (1.2) Fixed (2.1)	**$SI_{R1,k}$**	**$SI_{R2,k}$**	**$SI_{R3,k}$**	**GS_k**
42	1st floor on, fixed, louvres, superficial, PV, fan	0.86	0.72	0.82	0.81
43	1st floor on, fixed, louvres, superficial, PV, LED	0.86	0.72	0.78	0.78
44	1st floor on, fixed, louvres, superficial, WIND, LED	0.70	0.72	0.78	0.76
45	1st floor on, fixed, exterior curtains, bottles, waste, PV, fan	0.79	0.85	0.74	0.76
46	1st floor on, fixed, exterior curtains, bottles, waste, PV, LED	0.79	0.85	0.69	0.74
47	1st floor on, fixed, exterior curtains, bottles, waste, wind, LED	0.63	0.85	0.69	0.72
48	1st floor on, fixed, exterior curtains, other containers, waste, PV, fan	0.57	0.93	0.70	0.73
49	1st floor on, fixed, exterior curtains, other containers, waste, PV, LED	0.58	0.93	0.65	0.70
50	1st floor on, fixed, exterior curtains, other containers, waste, wind, LED	0.41	0.93	0.65	0.68
51	1st floor on, fixed, exterior curtains, superficial, PV, fan	0.90	0.67	0.68	0.70
52	1st floor on, fixed, exterior curtains, superficial, PV, LED	0.91	0.67	0.64	0.67
53	1st floor on, fixed, exterior curtains, superficial, LED	0.74	0.67	0.64	0.65
54	1st floor on, fixed, exterior curtains, small, PV, fan	0.48	0.67	0.73	0.69
55	1st floor on, fixed, exterior curtains, small, PV, LED	0.49	0.67	0.68	0.66
56	1st floor on, fixed, exterior curtains, small, wind, LED	0.32	0.67	0.68	0.64
57	1st floor on, fixed, sun sail, bottles, waste, PV, Fan	0.66	0.80	0.74	0.74
58	1st floor on, fixed, sun sail, bottles, waste, PV, LED	0.67	0.80	0.70	0.72
59	1st floor on, fixed, sun sail, other containers, waste, PV, fan	0.50	0.84	0.74	0.73
60	1st floor on, fixed, sun sail, other containers, waste, PV, LED	0.50	0.84	0.70	0.71
61	1st floor on, fixed, sun sail, superficial, PV, fan	0.84	0.64	0.67	0.68
62	1st floor on, fixed, sun sail, superficial, PV, LED	0.84	0.64	0.63	0.65
63	1st floor on, fixed, sun sail, small, PV, fan	0.21	0.55	0.73	0.64
64	1st floor on, fixed, sun sail, small, PV, LED	0.22	0.55	0.68	0.61
	Alternatives from the First Floor on (1.2) that Move (2.2)	**$SI_{R1,k}$**	**$SI_{R2,k}$**	**$SI_{R3,k}$**	**GS_k**
65	1st floor on, movable, louvres, superficial, PV, fan	0.76	0.70	0.86	0.82
66	1st floor on, movable louvres, superficial, PV, LED	0.77	0.70	0.86	0.82
67	1st floor on, movable, exterior curtains, bottle, waste, PV, fan	0.68	0.83	0.81	0.80
68	1st floor on, movable, exterior curtains, bottle, waste, PV, LED	0.69	0.83	0.77	0.78
69	1st floor on, movable, exterior curtains, other containers, waste, PV, fan	0.46	0.90	0.81	0.80
70	1st floor on, movable, exterior curtains, other containers, waste, PV, LED	0.47	0.91	0.77	0.77
71	1st floor on, movable, exterior curtains, superficial, PV, fan	0.80	0.65	0.75	0.73
72	1st floor on, movable, exterior curtains, superficial, PV, LED	0.80	0.65	0.71	0.71
73	1st floor on, movable, exterior curtains, small, PV, fan	0.40	0.66	0.80	0.73
74	1st floor on, movable, exterior curtains, superficial, PV, LED	0.40	0.66	0.76	0.70
75	1st floor on, movable, sun sail, bottle, waste, PV, fan	0.60	0.79	0.77	0.76
76	1st floor on, movable, sun sail, bottle, waste, PV, LED	0.60	0.79	0.73	0.73
77	1st floor on, movable sun sail, other containers, waste, PV, fan	0.44	0.83	0.77	0.75
78	1st floor on, movable, sun sail, other containers, waste, PV, LED	0.44	0.83	0.73	0.72
79	1st floor on, movable, sun sail, superficial, PV, fan	0.75	0.63	0.70	0.69
80	1st floor on, movable, sun sail, superficial, PV, LED	0.76	0.63	0.66	0.66
81	1st floor on, movable, sun sail, small, PV, fan	0.17	0.54	0.76	0.65
82	1st floor on, movable, sun sail, small, PV, LED	0.17	0.54	0.71	0.63
	Non-Logical Alternatives	**$SI_{R1,k}$**	**$SI_{R2,k}$**	**$SI_{R3,k}$**	**GS_k**
83	Ground floor, fixed, solid panels, cardboard, PV, fan	0.94	0.33	0.70	0.65
84	Ground floor, fixed, solid panels, cardboard, PV, LED	0.95	0.33	0.66	0.62
85	Ground floor, fixed, solar control glass, superficial,	0.54	0.37	0.42	0.42
86	Ground floor, fixed, solar control glass, plastic bags	0.54	0.30	0.47	0.44
87	Ground floor, movable, roller shutters, superficial, PV, LED	0.80	0.65	0.73	0.72
88	Ground floor, movable, solid panels, cardboard, PV, fan	0.84	0.31	0.70	0.64
89	Ground floor, movable, solid panels, cardboard, PV, LED	0.85	0.31	0.66	0.61
90	1st floor on, fixed, solid panels, cardboard, PV, fan	0.93	0.33	0.70	0.65
91	1st floor on, fixed, solid panels, cardboard, PV, LED	0.94	0.33	0.65	0.62
92	1st floor on, fixed, solar control glass, superficial,	0.54	0.37	0.42	0.42
93	1st floor on, fixed, solar control glass, plastic bags	0.54	0.30	0.47	0.44
94	1st floor on, movable, roller shutters, superficial, PV, LED	0.73	0.65	0.73	0.71
95	1st floor on, movable, solid panels, cardboard, PV, fan	0.82	0.31	0.70	0.63
96	1st floor on, movable, solid panels, cardboard, PV, LED	0.82	0.31	0.65	0.60
	Most Used Current Solar Control Device	**$SI_{R1,k}$**	**$SI_{R2,k}$**	**$SI_{R3,k}$**	
97	Exterior roller shutter	0,45	0,00	0,46	

Appendix E

Table A11. Abbreviations used in the text.

Abbreviations	Relevant Values
MSW	Municipal Solid Waste
AC	Air Conditioning
GMA	General Morphology Analysis
MCDM	Multi-Criteria Decision Making
MIVES	The Integrated Value Model for Sustainable Assessment
CCA	Cross-Consistency Assessment
AHP	Analytic Hierarchy Process
GSk	Global sustainability index
SIRi,k	Requirements satisfaction index
CIRi,k	Criteria satisfaction index
Vi,k	Value from the value function satisfaction
LED	Light-Emitting Diodes
DCV	Decreasing Concave
DL	Decreasing Lineal
ICX	Increasing Convex
IL	Increasing Lineal
PV	Photovoltaic
N/A	Not Applicable
UA	Unexpected Alternative

Table A12. Abbreviations for Equations (1) and (2).

Abbreviations	Relevant Values
A	The response value to Xmax
ki	Value that comes closer to the ordinate of the curve inflection point
Xalt	Each response to the indicator value function
Xm = Xmax	The maximum abscissa value considered for decreasing indicators
Xm = Xmin	The minimum abscissa value considered for increasing indicators
Ci	Value that closer to the abscissa value of the curve inflection point
B	Parameter that maintains the function within the 0 to 1 range

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Chapter 4.
Generate and Assess Sustainable IF alternatives for cases

For the sake of further investigations on the installable solar control devices, this doctoral research investigates IF layers as an innovative rehabilitation alternative, which, until now, has had outstanding performances in other architectural applications.

Accordingly, **Chapter 4** develops a new model to quantitatively assess the sustainability of five outstanding IF technologies when applied to optimize the discussed primary schools' architecture problems. This chapter rigorously covers **Phase 4** of this research thesis and is the final evaluation to define the most sustainable solution.

The results of this chapter have been collected in **Article C**: "New sustainability assessment model for Intelligent Façade Layers when applied to refurbishing school buildings skins".

4.1. Introduction

The post-occupancy analyses of the proposed solution in **Chapter 3**, consisting of adding an external layer on transparent parts of the classrooms' walls, that is discussed in the previous chapter, show that these passive devices can perform better to gain maximum solar heat during the cold seasons and daylight all year round.

This chapter provides a step forward in terms of movable solar control devices and introduces IFs to achieve maximum sustainability performance in the case studies. Intelligent façades are pioneering technologies in terms of optimizing energy consumption and comfort levels and reducing bills in the buildings [87]. These layers are designed to operate separately as a regulator of building metabolism, which is capable of energy, material, and information exchanges and to adapt themselves to changing external conditions and internal requirements. These layers are often connected to other devices including sensors, actuators, and command wires from a building management system [88–91].

However, their application in existing buildings is lowly developed, due to several economic and social challenges. Until now, the IF experiences that have been carried out have proven to be costly in the fabrication, assembling, and usage phases [92]. Aelenei et al. [93] defined the initial cost of intelligent materials as the most important problem in decision-making for IFs. Attia et al. [53] argued that the high investment and operational costs of IFs as the main disadvantages of these technologies. Reports on IFLs also declare that these developments simultaneously brought some negative impacts in terms of functional capabilities [56,94]. These reports do not show a high level of user comfort during post-occupancy analyses [95–97]. For instance, Zalejska-Jonsson [98], demonstrates that in low-energy buildings, tenants have some dissatisfaction regarding thermal comfort and air ventilation. Reinhart and Voss [99] found that in 88% of the cases, within 15 minutes, office workers manually retracted the blinds after the automated blind system had automatically lowered due to low acceptability for automatic blind systems.

In the case of public-school centers, their high occupancy levels and their economic constraints have forced administrators to invest in technologies that though are environmentally-friendly, are also highly efficient, low-cost and social-friendly.

To the candidate's best knowledge, developing IF systems with maximum satisfaction in terms of economic, environmental, and social factors for public school buildings requires highly efficient and comprehensive methodologies to address all mentioned considerations.

In this context, this chapter developed a novel integrated sustainability assessment model to assess and define the most sustainable IF alternatives for the specific case studies of this research thesis for the first time. The definition of this new model followed the combination of the MIVES and the Delphi, relying on literature, real projects, and sensitivity analyses. This new model defined boundaries, qualified the panel members, performed seminars, defined a requirements tree, assigned weights, defined and assessed alternatives, obtained the global and partial sustainability indexes, and finally selected the most sustainable IF alternatives for the case studies.

This chapter as a first step, and based on a specific unbiased protocol of the Delphi tool, selected 12 qualified experts from construction industry professionals, academic professors, educational administrators, and faculty members (see Table 3 in Section 4.4). This chapter then obtained experts' opinions based on a modified version of the Nominal Group Technique (NGT) [100] and face-to-face meetings, discussions between rounds or contact, and gathering their inputs via email.

The second step elaborated questionnaires that were distributed among the experts during the seminars. By following the recommended protocols of Delphi, 4 levels of questionnaires and seminars were performed to define a new requirements tree for MIVES that could assess innovative IFLs.

The third step defined five IF alternatives that are recently used in high-cost outstanding buildings, including A1) ETFE inflating cushion; A2) Bioreactor panel; A3) Ever-changing wind façade; A4) Kinetic PTFE layer; A5) TiO_2 covered thermoformed tile. Figure 2 in Section 4.4 shows the most representative components and architectural details for these five alternatives.

Step 4, theoretically applied the newly developed model and assessed defined alternatives to optimize the performance of the case studies based on 16 sustainability indicators of the requirements tree comprising: I1) fabrication & assembling cost; I2) annual maintenance cost; I3) annual operation cost; I4) dismantling cost; I5) energy consumption; I6) embodied carbon; I7) annual energy saving; I8) energy conversion efficiency; I9) annual blocked embodied carbon; I10) recyclability; I11) reusability; I12) fabrication & assembling easiness; I13) flexibility; I14) ventilation performance; I15) light performance; I16) user safety added value.

The model generated the global sustainability index (GS_k) for each alternative and then their partial indexes for their economic ($SI_{R1,k}$), environmental ($SI_{R2,k}$), and social requirements ($SI_{R3,k}$). Table 8 in Section 4.4 shows these global and partial satisfaction indexes for each alternative.

Alternative A4 has obtained the highest global index for the studied cases of public Spanish primary schools. This is mainly because A4 provides maximum thermal and visual comfort, along with its low-cost automatic and dynamic translucent blinds. These dynamic blinds are operating with energy-efficient linear jack screws that have low annual operation costs. However, the low environmental satisfaction index is due to its high embodied energy and embodied carbon. Moreover, the flexibility indicator results show that A4, which is connected and operating with a computer-controlled system, does not provide absolute comfort for users. On the other hand, alternative A5 has also high sustainability index due to its improved air quality and considerably reduced pollution concentration.

Finally, the main MIVES results showed that the extensive IF with a high level of responsiveness, low fabrication and maintenance costs, low embodied energy and carbon, high energy efficiency, high recyclable material, and with secure, healthy, and comfortable inner conditions is the perfect solution for Spanish public primary schools. By performing a sensitivity analysis in the last step, the candidate concluded that the results described above are robust.

4.2. Contribution to thesis

This chapter overcomes the lack of comprehensive assessments of IFs and develops a new model specialized in the sustainability assessment for these technologies within this thesis's boundaries. Allowing sustainability indicators to be further integrated into the design process will assist in knowing what the impacts of façades will be before they are developed and implemented; allowing stakeholders to eliminate unnecessary costs throughout the development and use phases, and; ensuring the technology will assist in the creation of a comfortable built environment.

Accordingly, the main contribution of this chapter is the definition of an innovative MIVES-Delphi assessment model able to quantify the sustainability of IFs. This innovative model ensures the most qualified experts and the most reliable data with minimum biases. This chapter successfully applied this new framework to develop a new low-cost optimized IF with the highest sustainability indexes adaptable to Spanish public primary schools.

The developed framework in this chapter has a special focus on the final production cost of these technologies. Hence, based on the previously developed waste-based solutions, this chapter framework also recommended reusing waste as a tool for continual improvement and a cost reducer due to reduced resource consumption. This new framework showed that an optimized IF for the case study should fulfill the following: a) be responsive to indoor and outdoor environment changes, b) incorporate renewable energy systems and be able to operate independently from energy sources, c) control the loss and the gains of thermal energy, d) provide an optimal visual comfort adjusted to conditions in a classroom and permit natural light to enter as well as stop undesired solar radiations, e) provide optimal olfactory comfort, reduce pollution concentration and permit natural ventilation, f) be adjustable and modifiable according to users' requirements, g) be able to incorporate reusable low-cost materials to reduce the production cost and increase environmental indicators satisfaction, h) be able to reuse the constituent technologies during their end of life phase, and finally i) be as simple and safe as possible to incorporate members of a school community during its assembling process.

4.3. Contribution from the candidate

In this **Chapter 4** the candidate develops a new comprehensive assessment methodology based on reviewing the state-of-the-art in **Chapter 2** and applied methodologies in **Chapter 1**. One of the main tasks of the candidate was defining the whole steps and phases of the model as setting boundaries, data treatment, and assessing IFs. Another important task was leading the writing of the scientific article as the main author. The general research question and its general scientific and social perspective were proposed by the candidate.

Considering the novelty of the innovative intelligent façade technologies, the "data collection" phase was the most challenging part for the candidate which had been carried out through communications and interviews with different innovative façade companies and researchers. Moreover, considering the case of Spanish primary schools, the extracted data have been converted to Spanish context using different Spanish database platforms mainly the BEDEC database [101].

The framework developed in this chapter proposed Delphi to supervise and verify the sustainability assessment process of IFs. Accordingly, the candidate, based on the Delphi protocols, has interviewed professionals from the Technical University of Munich, the Slovak University of Technology, Institute of Environmental Assessment and Water Research, the University of Cambridge, ISOLANA material company, Akustika company, Trespa Design Center, and SOMFY architecture company. These interviews have continued in 4 rounds and have been carried out through emails, video calls, and face-to-face meetings which provided a solid and rigorous base for developing a novel methodology.

The candidate conducted the literature search and wrote the general introduction. The co-authors collaborated throughout the elaboration of the paper to discuss both the organization and the main findings of the results and to provide answers to reviewers. The candidate also took part in giving insightful revisions and answers to reviewers.

4.4. Article C

This section presents the **Article C** of this research thesis. This article is the final evaluation of IF alternatives to define the most sustainable solution for studied samples.

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Original article

New sustainability assessment model for Intelligent Façade Layers when applied to refurbish school buildings skins

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ABSTRACT

In regard to increasing reports toward severe comfort problems and high energy consumption by educational buildings in many countries, a sustainable refurbishment for these edifices is urgently required. Using Intelligent Façade Layers as a protective cover with a variety of possible energy sources would be an innovative rehabilitation alternative, which until now has had outstanding performances in other architectural applications.

This research paper, overcoming the lack of comprehensive assessments on Intelligent Façades, develops a new model to quantitatively assess the sustainability of these façades when applied to optimize existing educational architecture. This model combines the multi-criteria decision-making MIVES method with the Delphi technique, relying on literature, real projects and sensitivity analyses. The model considers the main economic, environmental and social aspects in its steps: 1) model boundaries, 2) experts' qualification, 3) requirements tree, 4) weights assignment, 5) value functions, 6) sustainability indexes and 7) most sustainable alternatives. This model has been applied and validated in five Intelligent Façade Layers alternatives and three case studies at schools in Barcelona, Spain. This new approach proved highly reliable, showing the need for optimizations in both economic and environmental impacts applied to refurbishment scenarios. In this sense, future steps will design optimized alternatives.

Introduction

At present, the high environmental impact of human activities has severe consequences for our planet and our economies [1,2] and in consequence, governments prepare policies and laws to move towards a healthier environment. The construction sector is one of the most important causes of environmental impacts [3] as this sector consumes 32% of the planet's resources, 25% of the planet's water and 40% of the planet's energy [4–7]. In addition, this industry also generates 25% of the planet's solid waste and 35% of the total Greenhouse Gases (GHGs – Appendix H presents a complete list of abbreviations) [8,9]. Past studies show that in the course of achieving optimum economic, environmental and social performances, optimizing façades has the top priority among other elements in a building [10].

In some exemplary architecture cases, the implementation of Intelligent Façade Layers (IFL) has taken on an important role in both construction and refurbishment projects [11–14]. By incorporating these layers, energy and comfort performance is expected to increase by a) reducing transmission heat loss and b) increasing solar heat, daylight, natural ventilation, and solar gains control. In general about 97.6% of a building's energy and cost consumption comes from Heating, Ventilation, and Air Conditioning (HVAC), lighting, appliances, and general services [15], approximately 36% of which can be cut down by façade optimization [16,17]. Luo et al. [18] estimated that between 20% and 50% reduction in total energy consumption could be achieved by implementing appropriate building envelopes using Phase-Change Materials (PCM), Photovoltaic (PV) modules, thermoelectric modules, etc.

In the specific case of school centers, their building environment – comprising building infrastructure and environment – are critically important and can promote health or introduce harmful exposures that significantly affect children's well-being [19]. In this sense, the quality of an educational environment affects the learning process of the children who study in it [20,21]. High-quality school facilities have a measurable positive impact on pupils' ability, well-being, and knowledge by leading to increases up to 90% in skills and 86% in positive attitude changes [22]. Lighting, noise, educational spaces, coloring, inappropriate temperature, overcrowded classes, misplaced boards and inappropriate classroom layout are considered as the main architectural

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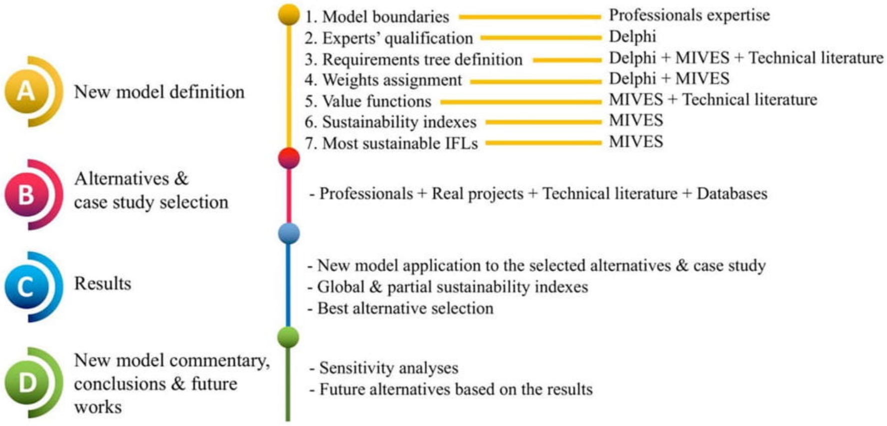

Fig. 1. Main phases, steps and methods followed in this research project.

elements that could affect students' learning process [23].

Until now, these IFL experiences have been carried out and proven to be costly in fabrication, assembling and usage phases [24]. Aelenei et al. [25] defined the initial cost of intelligent materials as the most important problem in decision making for IFLs. This author pointed out that this challenge diverts the focus from the essential benefits of the investment on IFLs. Attia et al. [26] clarified the high investment and operational costs of Intelligent Façades as one of the main disadvantages of these technologies. Reports on IFLs also declared that these developments simultaneously brought some negative impacts in terms of functional capabilities [27,28]. These reports do not show high level of user comfort during post-occupancy analyses [10,29–31]. For instance, Zalejska-Jonsson [15], demonstrated that in low energy buildings, tenants have some dissatisfaction regarding thermal comfort and air ventilation. Reinhart and Voss [32] found that in 88% of the cases, within 15 min, office workers manually retracted the blinds after the automated blind system had automatically lowered them showing a low acceptability for automatic blind systems. To the authors' best knowledge, these satisfaction incongruences are due to the lack of specific comprehensive methodologies to assess IFLs' sustainability. Architecture environmental and sustainability performance can be assessed using, for example, energy modeling, Life Cycle Assessment (LCA), Life Cycle Inventory (LCI) and Life Cycle Cost (LCC) simulations, and sustainability rating tools such as BREEAM or LEED [33,34]. The results of these worldwide-accepted methodologies indicate whether a building has achieved a certain level of environmentally-conscious design. The application of these methodologies requires available literature, data and/or observations [35,36]. However, as long as IFLs are relatively new, proven accessible data scarcely exists.

In this context, the main objective of this study is to find out if IFLs are a sustainable solution for the optimization of school buildings' façades, as well as quantify this hypothetical contribution. To this end, this research project develops a novel integrated sustainability assessment model and applies it to a specific case study for the first time. This new model incorporates all the aforementioned crucial indicators. The definition of this new model followed the Integrated Value Model for Sustainable Assessment (Modelo Integrado de Valor para una Evaluación Sostenible – MIVES) [37] and Delphi [38]. The first case study assessed using this new model aims to prove the aforementioned hypothesis. Thus, five exemplary IFLs that have been used recently in high-cost outstanding buildings are theoretically applied to optimize the façades on Barcelona public primary school buildings. Then this new model assesses this theoretical application. This manuscript is organized into six sections. Section 2 presents the applied methods, Section 3 describes the alternatives to assess them and their case study, Section 4 shows the results that are discussed in Section 5. Section 6 concludes this study and Section 7 presents future projects.

Methods

The methodology adopted in the present study selects the most sustainable IFL that has the following four phases: A) New model definition, B) Alternatives and case study selection, C) Results and D) New model commentary, conclusions and future projects. Fig. 1 shows these phases, their main steps and the methods and resources used to define the new model.

The first phase develops the new comprehensive model specialized in the sustainability assessment for IFLs within the boundaries in this project. To do so, this assessment follows the proved methods Delphi [39], MIVES [37,40–42] among others as explained in depth in the following sections. MIVES is a customizable and agile sustainable assessment model that enables overall assessment, comparison, and ranking of alternatives, compared to other decision-making methods as has been proved in numerous previous studies, though none of them have been about IFL. Simultaneously, Delphi method, is an internationally recognized method able to a) control and minimize possible bias, b) elicit and refine group of professionals, c) obtain reliable data and judgment from an expert on a specific topic, was used to collect the required data relevant to the decision-making problem [39]. MIVES models incorporate a requirements tree and the value function concept, by means of which researchers integrate the results obtained by each indicator to non-dimensional sustainable satisfaction values, even if the indicators have different measurement units [40].

This process began in the first phase by defining the new model boundaries, scope and limits based on literature studied. A group of experts was qualified as the panel members regarding Delphi protocols. Based on MIVES instruction, a preliminary list of criteria and indicators compiled from the available literature was prepared. Based on these gathered criteria, a questionnaire was elaborated, which during the seminars was distributed among the multi-disciplinary experts present to obtain their outlook on a) criteria and indicators to be included in selection of façade systems and b) comparative importance or relative weight of different criteria and indicators rated using a 0 to 100 scale. By following the recommended protocols in the Delphi method, 4 levels of questionnaires and seminars were performed to define a new requirements tree for a Multi-Criteria Decision Making (MCDM) [43] tool that could assess innovative IFLs. These identified requirements, divided into three main categories of economic, environmental and social impacts, are discussed in detail in the following section. The researchers in this study have completed the next step to define the value functions to convert the qualitative and quantitative variables into a 0 to 1 satisfaction scale, obtaining global and partial sustainability indexes and finally selecting the most sustainable IFL alternatives.

The next phase selects the studied IFL alternatives and the case study. The third phase starts to assess the previously defined alternatives sustainability using the new model developed in first phase. The final phase discusses the results, includes sensitivity analyses, draws conclusions and proposes future projects as explained in detail in the following sections.

As Fig. 1 presents, this research project relied on professionals' experience in step 1, applied Delphi in steps 2 to 4, MIVES in steps 3 to 7 and relied on technical literature in steps 3 and 5.

Model boundaries

Based on the initial problem and its context, the limits for this research project are the IFLs applied to refurbish the skins on public educational buildings. These refurbishments include façades, which are the first elements to degrade and lose their functionality over time [44]. This study focuses on the façade refurbishment possibilities with minimum necessities to demolish and have construction works. Refurbishment includes the thermal, light and energy performance that effects both exterior and interior spaces. However, this study does not consider IFL effects on the acoustic performance by a façade. The acoustic performance is affected by the total elements in a façade while this study focuses on refurbishment possibilities which are applicable with minimum changes to the main elements as already mentioned. This study considers IFLs as the definition provided in the introduction, considering both opaque and transparent parts. This research project excludes new constructed buildings as well as high-cost architectural icons. Only existing edifices in high need for façade rehabilitation are included. This was the main reason for selecting public governmental school edifices which have been constructed during recent years in limited time frames and under tight budgets.

Experts' qualification

This step uses a strategic and unbiased method to qualify expertise level of panel members which is a crucial subject in Delphi [38]. In this study, the authors created a set of specific expertise requirements based on the objectives and limitations in this study to receive a good recognition by experts. After making a list of construction industry professionals, academic professors, educational administrators, and faculty members, this project suggests that the chosen panelists must meet at least four specific requirements listed in Appendix A. In order to appraise the final qualification for experts, Delphi suggests developing a relative point system [45] listed in Appendix B. This study chose those panelists who score at least 2 points in four different achievement categories. This qualification process by experts in Delphi assumed that reducing bias to its lowest level due to the experts' outstanding experience and/or knowledge and this is the potential strength that Delphi has [46]. However, various sources for bias still can exist. This research study applied specific controls to decrease bias as far as possible, as presented in Appendix C. In addition, in order to obtain experts' opinions, this research article applied a modified version of the Nominal Group Technique (NGT) [47], so that the experts delivered their feedback during face-to-face meetings, discussions between rounds or contact and gather their inputs via email. Nevertheless, the use of this NGT version permitted bias reduction as required.

Requirements tree definition

Following MIVES, a suitable requirements tree with exclusively the most significant and discriminatory requirements and criterion was established from the literature and experts feedback [48]. Fig. D.1 in Appendix D presents a theoretical schema for MIVES requirements trees. In this project, this tree was generated by taking into account the targeted sample Spanish schools [49]. This requirements tree was established during two rounds of integrated questionnaire surveys based on Delphi to obtain professional inputs regarding the essential sustainable indicators that can be incorporated into this MCDM model. In this first round, a brief input by the panelists about the proposed requirements tree was required based on provided instructions, boundaries and additional considerations. The second round resulted in a defined requirements tree after applying the panelists' inputs in both rounds.

Weights assignment

In requirements trees of MIVES models, weights reflect the importance and the strength for the requirements, criteria, and indicators [50] as presented in Fig. D.1 in Appendix D. In this study, these weights have been assigned following Delphi protocols and can be done by the direct assignation or the Analytical Hierarchy Process (AHP) [47]. In order to achieve consensus between experts, Delphi suggests different rounds of surveys. During the first round, the panelists were provided with defined requirements tree in step 1.2. and later with instructions on how to assign the weights with the purpose to prioritize them. Panelists were asked to respond to the following questions: "Imagine if you are an administrator in a school in Barcelona, which Intelligent Façade Layer would you choose? What factors do you think should be taken into account?" Subsection 4.3 presents the weights assigned by the panelists in both rounds. According to the Delphi method [39], a consensus is achieved when the median absolute deviation is less than 10% as weights can adopt values between 0% and 100%. Equation (1) shows the median absolute deviation, which is implemented due to its lower biased impacts.

$$\textit{Median absolute deviation} = \frac{\sum_{i=1}^{n}|x_i - median|}{n} \tag{1}$$

Where n is the total number of data items and x_i is the data i.

Delphi requires a second round if consensus cannot be achieved in the first round [39]. Median response from first round should be provided for panelists as feedback for round 2. In order to measure consensus, as in previous research projects, this project considers consensus achieved when absolute deviation is within one unit on a 1–10 scale. This occurs because absolute deviation measures vary in response to median. In this study, median is also used to define the assigned weights because median has less probability to be influenced by biased results.

Value functions definition

These indicators can have dissimilar qualitative or quantitative variables, or different units and scales. As previously explained, MIVES solves any such variables by using value functions, which are single mathematical functions for each indicator that transform the indicator results into a single satisfaction scale from 0 to 1 [51].

Global and partial indexes and most sustainable IFLs

Defining sustainable global and partial indexes for each alternative is the last step in the MIVES methodology. Equation (2) presents the partial satisfaction indexes for each requirement $SI_{Ri,k}$ considering same requirement weight.

$$GS_k = \sum_{i=1}^{j} \lambda_{Ri,k} . SI_{Ri,k} \tag{2}$$

Each $SI_{Ri,k}$ is obtained by adding up their criteria $CR_{i,k}$ considering the weight of same requirement. And each $C_{Ri,k}$ is obtained by adding up their indicators I_k, considering the weight of same criteria, as presented in Fig. D.1 in Appendix D. Finally, relying on these results and their

Table 1
Main parameters and relevant values used to select the IFL alternatives [52–59].

Parameters	Relevant Values
Position	External (EX); Internal (IN)
Responsiveness	Fixed (F); Hybrid (HY); Manual (M); Mechanical (MC)
Treatment system	Light (L); Solar Radiation (SR); Temperature & Air (TA); View (V)
Renewable energy system	Hydro-Generator (HG); Hydro-Thermal (HT); Photovoltaic (PV); Wind-Generator (WG)
IFL typological system	Bio-Façade (BF); Curtain Panels (CP); Double skin façade (DSF); Kinetic Façade (KF); Solar Façade (SF)
Filling material	Glass (G); Polymeric (P); Smart Material (SM); Textile (T); Waste-based (WB)

rigorous discussion, the researchers can decide which of these assessed alternative or alternatives would be better to optimize the façades on the target school buildings.

Selected alternatives and case study

This section explains and justifies the alternatives that were selected to be evaluated using the new sustainability assessment model and the selected case study to which these alternatives were theoretically applied in depth. The alternatives are real IFL cases but have not been applied to the case study yet. These alternatives have been chosen according to their proximity to case studies sustainability requirements, which are closely related to their actual implementations, material, and technical principles, regardless of their geographical location. This study assessed a theoretical but feasible and realistic application for these alternatives to the case study. This phase also selected the case study in which these alternatives were going to be theoretically applied.

Selected alternatives

The first application of this model aimed to assess the sustainability of only a few exemplary IFLs in depth rather than a general overview of numerous alternatives. Nevertheless, these selected alternatives were representative of a broader sample of 21 IFL cases that are listed in Table E.1 in Appendix E which was the result of a simplified literature review on exemplary IFLs. This selection also relied on the knowledge and expertise from the authors and professionals involved in the design and construction of these IFLs, who took into account the limitations and objectives in this case study. Thus, this study chose alternatives that were representative of the different IFLs available as well as feasible for the façade refurbishment in the case study. To do so, the authors defined the main parameters for selecting the IFLs which they were going to assess, along with their value ranges. Table 1 shows the six parameters and the relevant values used to select the most representative IFL alternatives.

The first parameter is about the IFL position and considers two different values: external or internal. Considering the previously mentioned boundaries for this study, the installation of an IFL must cause minimum deterioration on a school's façade. Accordingly, this first parameter disregards integrated IFLs that merge with the elements of main façade. The second parameter is responsiveness and movement type by an IFL that includes fixed, hybrid, manual and mechanical options. This study focuses on devices with minimum price and maximum capability to ensure student comfort and, therefore, this project does not include energy-free and/or self-actuated IFL. The third parameter is the IFL treatment or management system, which can be: treatment with inside light, solar radiation, temperature and view. As already mentioned in Subsection 2.1, this study does not consider acoustic performance by IFLs. The fourth parameter considers the integrated systems in IFLs, which provide renewable energy for the building's or IFL's own operation. This parameter includes all current feasible renewable energy systems. Five different possible IFL types are analyzed in fifth parameter as shown. The sixth parameter is the IFL's main filling material and has five possible values: 1) different types of glass; 2) polymer-based synthesis as Polytetrafluoroethylene (PTFE), Ethylene Tetrafluoroethylene (ETFE); 3) two different categories of smart materials include energy-exchanging and property-changing materials; 4) textiles and 5) waste materials being as expanded polystyrene, paper, paperboard, tetra bricks and plastic bags. This process of selecting alternatives shows the various designs that IFL technologies can have, in terms of structure, appearance, materials, components and layers, among others.

Correspondingly, out of the 21 studied IFL alternatives, identifying the constraints confirmed five alternatives: A1) ETFE inflating cushion developed for media-tic buildings in Barcelona [60], A2) Bioreactor panels installed in BIQ houses in Hamburg [61], A3) Ever-changing PC show built for San Francisco Public Building Utilities [62], A4) Kinetic PTFE Mashrabiya layer developed for Al Bahar Tower in Abu Dhabi [63] and A5) TiO_2 covered thermoformed tiles installed in Mexico City's Manuel Gea Hospital [64]. These chosen alternatives have various environmental conditions and are composed by several technologies. All selected alternatives are external due to their more positive effects on thermal performance in an indoor environment rather than internal IFLs from professional inputs. Some of these alternatives self-actuate while others operate by different stimulants. Table 2 lists the general features for these five alternatives.

Fig. 2 displays the most representative components and architectural details for these five alternatives while Appendix F shows the main detailed information for these alternatives. These details have been studied based on data and information obtained from the associated companies, factories, and executors of the real buildings. Other architectural information and details have been collected from different updated databases and literatures.

Selected case study and sample

At present, in Europe, many school buildings have deficiencies such as excessive energy consumption and emissions, increased maintenance costs, and low comfort levels that worsen pupils' well-being and learning processes [74,75], contrary to the positive examples presented in the introduction. During recent years, the number of reports regarding current educational architectural conditions and their high environmental impact have increased [76–79]. For instance, in most territories in Spain – of which Catalonia and Barcelona are an example –

Table 2
Defined alternatives general features.

	Alternative	Location	Y	Ps	Rp	Tr	Rs	Ty	Fm	Ref
A1	ETFE inflating cushion	Media TIC Barcelona	2009	EX	MC	TA, L, SR	–	KF	P	[60,65]
A2	Bioreactor panels	BIQ house, Hamburg,	2013	EX	HY	TA, V, L, SR	HT	BF	G	[54,66,67]
A3	Ever-changing PC show	SFPUC San Francisco	2012	EX	F	L, SR, TA	WG	DSF	P	[67–69]
A4	Kinetic PTFE Mashrabiya layer	Abu Dhabi, Albahar tower	2012	EX	MC	TA, V, L, SR	–	KF	P	[70,71]
A5	TiO_2 covered thermoformed tiles	Hospital General Dr. Manuel Gea, Mexico City	2013	EX	F	TA, V, L, SR	–	CP	P	[64,72,73]

Y: year; Ps: position; Rsp: Responsiveness; Tr: Treatment; RS: Renewable system; Ty: Type of IFL; Fm: Filling material; Ref: References; External (EX); Hybrid (HY); Mechanical (MC); Fixed (F) Temperature & Air (TA) ; View (V) ; Light (L) ; Solar Radiation (SR); Wind-Generator (WG); Hydro-Thermal (HT); Double skin façade (DSF); Curtain Panels (CP); Kinetic Façade (KF); Bio-Façade (BF); Polymeric (P); Glass (G).

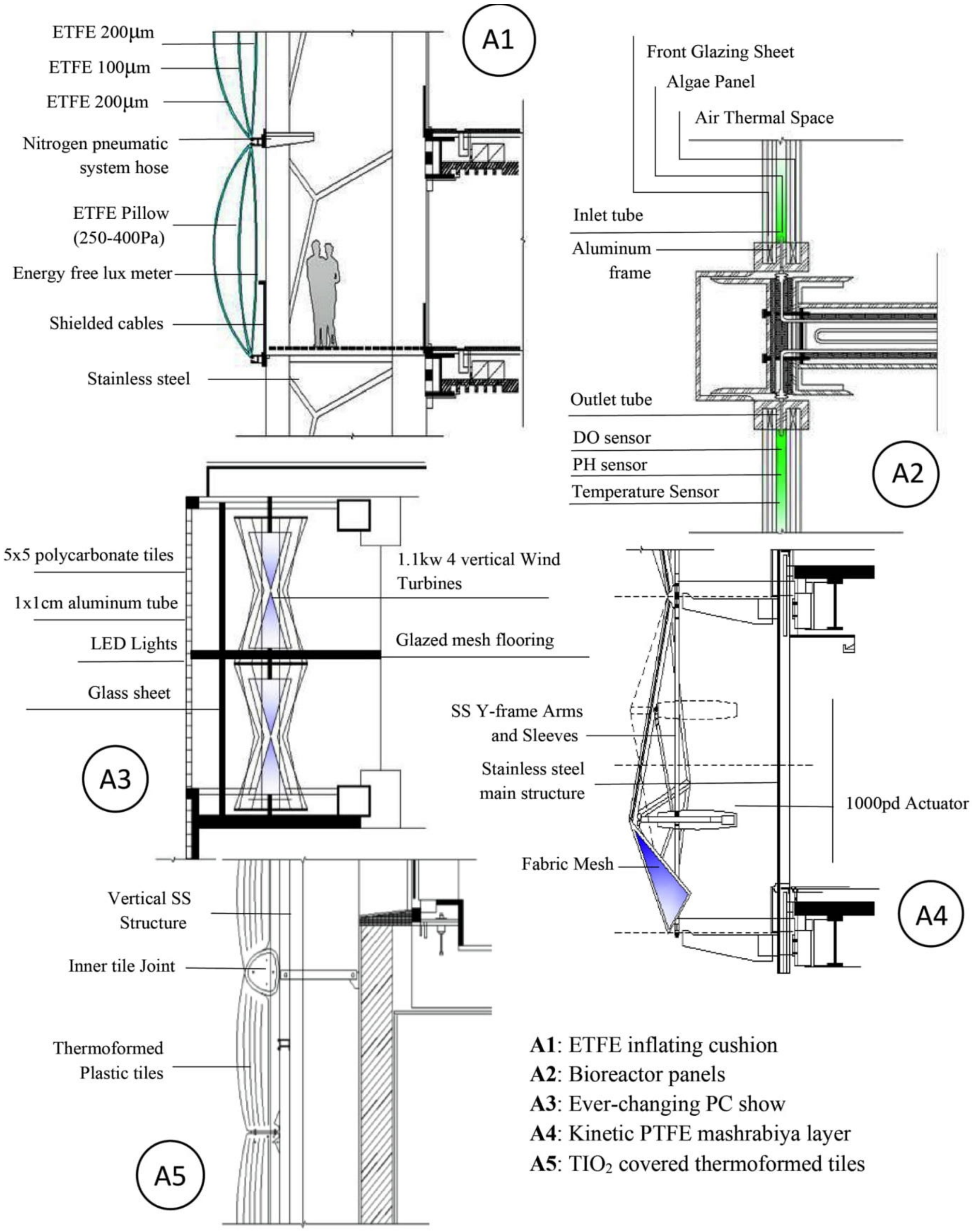

Fig. 2. Most representative details for the five defined alternatives.

Table 3
Qualified panel members and their expertise area.

N	Expertise area	Country	Organization	N	Expertise area	Country	Organization
1	Automation	Germany	University	**7**	Sustainability	Spain	University
2	Renewable energy systems	UK	University	**8**	Pedagogue	Spain	School
3	Energy efficiency	Spain	University	**9**	Environmental expert	Spain	Research Center
4	Intelligence	Spain	Façade Develop company	**10**	Innovative façade architecture	Spain	University
5	Education specialist	Spain	Educational research center	**11**	Structural Morphology architecture	Italy	Research Center
6	Education specialist	Greece	University				

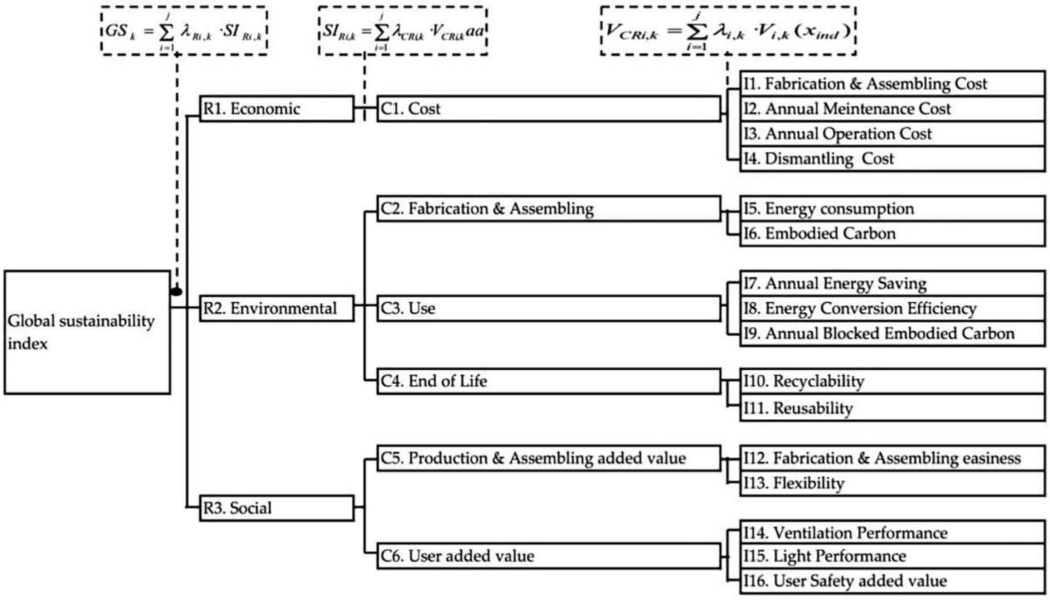

Fig. 3. MIVES tool defined requirements tree.

an important amount of school buildings are in urgent need to improve their façades to meet sustainability requirements [80]. The analyses show that in Spain schools use 84.6 kWh/m^2, which is still in the highest levels in Europe [81–84]. Moreover, psychological assessments on pupils in Spanish primary schools proved that they have suffered many discomforts due to improper thermal and lighting environments in their classrooms [49]. In addition, the air leakage by a glazed area with open shutters must be significantly lower than 0.5 l/s per m^2 [10], which Spanish schools often do not meet. A good solution could be to sustainably refurbish these schools, which could lead to improvements in their life cycles via reduced costs [85], aesthetics performance, energy efficiency, hazards control, comfort and above all their costs [13]. This refurbishment, as opposed to demolishing and building new ones, will contribute to a lower carbon impact [86]. One of the accepted approaches is adding an extra layer on the glazed parts of façades, consequently leading to a lower U-value, energy consumption and emissions level. However, this extra layer causes a reduction in passive solar heat gained during the heating season and reduces daylight all year round. Recent simulations show that a significant improvement in light by 70–150% can be achieved by using dynamic shading façade systems [87]. These are strong arguments for IFLs [53] to optimize comfort and energy performance in schools.

Therefore, this project studies primary educational centers, where children aged 6 to 12 study in grades 1–6. However, in order to be able to carry out a rigorous study, the researchers defined an initial smaller representative sample. This simplified set are the public primary schools located in three representative municipalities within the greater metropolitan Barcelona area. These sample characteristics and the satisfaction levels experienced by their pupils was evaluated in depth in previous studies [49,80], which confirmed that these schools are representative of the primary Spanish schools in needs of refurbishment [49].

Results

This section presents the results by applying the new model presented in the previous section to assess the selected IFL alternatives theoretically applied in this case study. This first application of the model aims to test the hypothesis of this study.

Qualified experts

A diverse group of highly qualified and well-rounded experts was identified to carry out rigorous IFL research based on the protocol mentioned in the first step in the last section. This study defined a panel of 11 members that had distinguished themselves as experts on the topic. Table 3 presents background information for these qualified panelists, such as their expertise.

Requirements tree

Fig. 3 presents the established sustainability requirements tree with its criteria and indicators ($\lambda_{Ri,k}$, $\lambda_{Cri,k}$, $\lambda_{i,k}$), which was defined following Delphi as explained in Subsection 2.3. This requirements tree has

Table 4
Median, mean, median absolute deviation and consensus for the first round in the survey.

		Weights of experts (%)											Median (%)	Mean	Absolute Deviation	Consensus
		1	2	3	4	5	6	7	8	9	10	11				
R1	Economic	40	50	25	34	30	30	40	40	20	20	40	34	34	7.72	YES
R2	Environmental	30	30	40	33	40	30	30	30	50	50	35	33	36	6.18	YES
R3	Social	30	20	35	33	30	40	30	30	30	30	35	33	31	3.8	YES
C1	Cost	100	100	100	100	100	100	100	100	100	100	100	100	100	0	YES
C2	Fabrication & assembling	20	30	30	25	20	25	50	40	20	20	30	25	28	6.81	YES
C3	Use	50	50	30	50	30	60	20	40	50	50	40	50	43	10	YES
C4	End of Life	20	20	40	25	50	15	30	20	30	30	30	30	28	7.27	YES
C5	Production & Construction value	30	60	45	25	50	30	30	40	50	50	40	40	41	9.09	YES
C6	User added value	70	40	55	75	50	70	70	60	50	50	60	60	59	9.09	YES
I1	Fabrication & Assembling cost	20	20	30	50	20	25	50	35	20	20	40	25	30	9.54	YES
I2	Maintenance cost	25	25	20	20	30	50	30	25	40	40	25	25	30	6.81	YES
I3	Operation cost	35	45	30	10	30	15	10	30	20	20	25	25	25	8.63	YES
I4	Dismantling cost	20	10	10	20	20	10	10	10	20	20	10	10	15	4.54	YES
I5	Energy consumption	40	60	50	50	60	70	50	50	30	40	50	50	50	7.27	YES
I6	Embodied carbon	60	40	50	50	40	30	50	50	70	60	50	50	50	7.27	YES
I7	Energy saving	33	50	40	50	30	50	40	40	50	20	50	40	41	7.54	YES
I8	energy conversion efficiency	33	30	30	25	30	30	20	30	30	40	20	30	29	4	YES
I9	Blocked embodied carbon	34	20	30	25	40	20	40	30	20	30	30	30	29	5.36	YES
I10	Recyclability	50	30	50	25	50	30	40	30	40	20	40	40	37	8.63	YES
I11	Reusability	50	70	50	75	50	70	60	70	60	80	60	60	63	8.63	YES
I12	Production & assembly easiness	40	30	60	50	40	30	80	40	60	70	40	40	49	12,72	**NO**
I13	Flexibility	60	70	40	50	60	70	20	60	40	30	60	60	51	12,72	**NO**
I14	Ventilation performance	33	30	33	33	30	30	40	33	30	40	30	33	33	2.09	YES
I15	Light performance	33	35	33	33	30	40	40	33	40	50	30	33	36	4.18	YES
I16	User safety added value	34	35	34	34	40	40	20	34	30	10	40	34	32	5.54	YES

different levels. The economic, environmental and social requirements have been defined in the first level. In the second level, the criteria are stated, which organize concepts and provide a useful structure for the analysis of each alternative. Finally, indicators are stated and each one has its measurable variable that has been used to quantify each IFL alternative. In order to avoid an excessive number of indicators, this research project considered the indicators with the highest variable values.

The following paragraphs describe in detail the indicators considered and those disregarded. Economic indicators are based on five LCC phases which assess production, assembly, maintenance, operation and dismantling cost. The time indicator is not included because it is a boundary condition. These IFLs are mountable and must be designed and assembled off-site and can be applied during schools' non-class hours so do not affect the centers' day-to-day activities. I1 measures the manufacturing and assembling cost for the system in €/m^2layer both off-site and on-site in Barcelona city. I2 evaluates the maintenance cost, including cleaning and regular inspection costs, in €/m^2layer/annually in Barcelona. I3 measures the hypothetical cost for the annual energy consumed by the IFL for its own operation in €/m^2layer, disregarding energy which can be saved or generated by each layer. I4 is associated with the end of life criteria and measures deconstruction and demolition costs for the IFL system in €/m^2layer in Barcelona.

The requirements tree is based on five LCA phases in order to evaluate potential impacts of production, transportation, assembling, use and waste management for IFL. I5 assesses the amount of energy required to manufacture and assemble each layer in KWh/m^2layer. I6 considers CO_2 emissions during manufacture and assembling phase in TCO_2/m^2layer. I7 measures the amount of energy that can be saved in KWh/m^2layer/annually. This indicator analyzes the U-value and the responsiveness by each layer in controlling solar radiation and heat during summer and winter and providing thermal comfort. I8 is energy conversion efficiency which evaluates the ratio between the useful output and input energy of each layer during the usage phase [88], in KWh/m^2layer/annually. I9 considers the amount of emissions, which are prevented or blocked by saving and/or generating energy by each layer during the usage phase in TCO_2/m^2layer/annually. I10 assesses the possible recyclable rate for each layer and ensuing solid wastes. I11 assesses the possible reusable rate for each layer for other projects instead of recycling or sending waste to a landfill. As part of the environmental indicators, water consumption is not considered; in all cases, water consumption accounted for less than 0.01% of the whole life cycle. This requirement does not include availability and resource consumption because most IFLs are mainly composed of recyclable items, not raw materials, for which indicators I10 and I11 are more important. And MIVES requirements tree exclusively requires including the most crucial indicators as previously explained.

The five social indicators analyze the values that alternatives can provide for primary students; these include safety values, construction values, appearance and different dimensions of comfort levels. I12 assesses the value for each layer based on production and assembling ease depending on a system being low-tech or high-tech, plus its simplicity. I13 evaluates the flexibility for each façade layer and repercussion for each façade typology in the rental price based on the novelty of a layer's systems, appearance, reliability, and popularity. I14 evaluates placements and movements for each layer's components in order to transfer and direct the wind direction to inside a room in order to provide fresh air and natural ventilation as a double skin façade. This indicator also evaluates the transformability performances for each layer. I15 measures the accessed favorable natural light based on the ability a layer has to absorb light, its transparency level, and its ability to prevent glare. I16 assesses the safety level for each Intelligent Layer in accordance with educational architecture standards. In this regard, this indicator evaluates fire resistance, durability, and other possible risks an alternative has. Safety values such as workers' safety, firefighter accessibility, security against intrusion and vandalism were not considered because these issues are related to the whole building environment and this report focuses on outer IFLs.

Table 5
Median, mean, median absolute deviation and consensus for the second round in the survey.

		Weights of experts (%)											Median (%)	Mean	Absolute deviation	Consensus
		1	2	3	4	5	6	7	8	9	10	11				
I12	Production & assembly easiness	40	30	40	35	40	30	50	35	50	50	50	40	41	6,36	YES
I13	Flexibility	60	70	60	65	60	70	50	65	50	50	50	60	59	6,36	YES

Table 6
The main parameters and value functions for each indicator.

	UNIT	X_{max}	X_{min}	C	K	P	Shape	References
I1	€/m^2	4000	300	1500	0.01	2.5	DCvx	[89–94]
I2	€/m^2	15	0	5	0.01	1	DL	[95–97]
I3	€/m^2	10	0	5	0.01	2.5	DCvx	[96,98,99]
I4	€/m^2	200	50	100	0.01	1	DL	[96,100,101]
I5	KWh/m^2	4000	500	2000	0.01	1	DL	[82,102]
I6	TCO_2/m^2	2	0.1	1	0.01	2.5	DCvx	[65]
I7	Point %	90%	30%	50	0.01	2.5	ICvx	[16,27,52,103]
I8	Point %	100	− 50	20	1	0.8	ICcv	[28,67,104,105]
I9	TCO_2/m^2	1	0	0.5	1	0.6	ICcv	[65,106,107]
I10	Point %	100	80	80	1	2.5	ICvx	[8,108,109]
I11	Point %	100	20	30	1	0.6	ICcv	[85,110]
I12	Point1-10	10	0	3	1	1.5	S-shape	[49,111,112]
I13	Point 1–10	10	5	7	1	0.6	ICcv	[44,53,29,31,32,113]
I14	Point 1–10	10	0	5	0.2	2.5	ICvx	[21,53,79,114]
I15	Point 1–10	10	0	5	0.2	2.5	ICvx	[20,49,53,77]
I16	Point 1–10	10	5	6	0.2	2.5	ICvx	[49,77,115]

Legend: DCVx—Decreasing Convexly; DL—Decreasing Lineal; ICvx—Increasing convexly; ICcv—Increasing concavely; S-shape—Increasing convexly to concavely.

Assigned weights

As presented in Table 4, during the first round in the survey, out of all requirements, criteria, and indicators, two indicators did not meet the consensus prerequisite. The variations in the weights assigned by the experts reflect differences in their preferences, especially in a new field in which there is no established formal knowledge. As expressed in their weights, some panelists think that production and assembling ease for IFLs must be placed over the flexibility and assigned higher weights to the production and assembling easiness indicator. However, some panelists believed that flexibility should be preferred to production and assembling easiness because it is more socially-friendly. In consequence, there was a second round in the survey.

During this second round, the panelists were requested to reconsider their assigned weight only for indicators I12 and I13 by providing median for weights for each one. Four panelists described the rationale behind their assignments. Table 5 presents the resulting weights for Indicators I12 and I13 during the second round.

This second round reached consensus in all requirements tree because I12 and I13 satisfied the consensus requirement. The values reached for the mean are the resulting reference weights for the MIVES developed for this study, which will be used to assess the IFL alternatives.

Value functions

This step presents the 16 indicators' value functions that depend on five parameters, which determine the function, shape and, in consequence, how each indicator value corresponds to the 0 to 1 satisfaction scale. As an example, Equation (3) calculates the value function for indicator I1, which has a decreasing convex shape (DCvx). Equation (3) illustrates the previously mentioned parameters: A = 0 is the response value to Xmax; ki = 0,01 comes closer to the ordinate of the curve inflection point; Xalt = X is each response to the indicator I1; Xm = Xmax = 4000 €/m^2 is the maximum abscissa value considered for I1 in this indicator because it is decreasing, if it were increasing it would be Xm = Xmin; Ci = 1500 €/m^2 comes closer to the abscissa value of the curve inflection point. The form factor for this concave curve is 2.5.

Table 7
Main architectural features for five defined alternatives based on developed requirements tree.

	ETFE inflating cushion	Bioreactor panels	Ever-changing PC show	Kinetic PTFE Mashrabiya layer	TiO_2 covered thermoformed tiles	References
I1	2225,40€/m^2	3503,58€/m^2	1584,46€/m^2	436,72 €/m^2	330,38€/m^2	[63,108,119–124]
I2	3,34€/m^2/a	12.68€/m^2/a	8,84€/m^2/a	0.68€/m^2/a	0.27€/m^2/a	[63,119,120,124,125]
I3	0,91€/m^2/a	0.62€/m^2/a	3.1901€/m^2/a	0.00042€/m^2/a	0	[63,108,120]
I4	144,56€/m^2	174,61€/m^2	157,67€/m^2	76,18€/m^2	56.32€/m^2	[63,108,120]
I5	2780.6 KWh/m^2	2742.39 KWh/m^2	3489.28 KWh/m^2	2561.87 KWh/m^2	536.63 KWh/m^2	[115,126–136]
I6	0.648TCO_2/m^2	0.9561 TCO_2/m^2	0.8643 TCO_2/m^2	1.2696 TCO_2/m^2	0.1078TCO_2/m^2	[126,127,129,136–140]
I7	73%	85%	51%	51%	37%	[63,124,125,141–144]
I8	− 0.073%	98.38%	91.69%	− 0.039%	0	[69,145–149]
I9	0.037TCO_2/m^2/a	0.069TCO_2/m^2/a	0.157TCO_2/m^2/a	0.47TCO_2/m^2/a	0.011TCO_2/m^2/a	[148,150–154]
I10	99.86%	92.80%	95.95%	99.17%	99.92%	[124,128,149,155–159]
I11	21.67%	39.44%	81.21%	41.88%	23.48%	[160,161]
I12	0.07	0.37	0.59	1.58	0.44	[120,136]
I13	7.5	9.4	5.75	8.2	7.5	[70,124,136,162–165]
I14	5	9.5	3	8.25	2.75	[63]
I15	8	8	8	7.5	8	[166–168]
I16	8	7.33	10	9	7	[124,168]

Table 8
Resulting sustainability indexes for defined alternatives.

	Alternative	SI_{R1k}	SI_{R2k}	SI_{R3k}	GS_k
A1	ETFE inflating cushion	0.54	0.46	0.44	0.48
A2	Bioreactor panels	0.29	0.63	0.60	0.50
A3	Ever-changing PC show	0.37	0.48	0.43	0.43
A4	Kinetic PTFE Mashrabiya layer	0.93	0.50	0.68	0.70
A5	TiO_2 covered thermoformed tiles	0.98	0.54	0.41	0.65

$$V_{I^1} = A + B.\left[1 - e^{-Ki\left(\frac{|Xalt - Xm|}{Ci}\right)^{Pi}}\right] = B.\left[1 - e^{-0.01.\left(\frac{|X-4000|}{1500}\right)^{2.5}}\right] \quad (3)$$

In Equation (4) Xmin = 300 €/m^2, which is the minimum abscissa value considered for I1.

$$B = \left[1 - e^{-Ki\left(\frac{|Xmax - Xmin|}{Ci}\right)^{Pi}}\right]^{-1} = \left[1 - e^{-0.01.\left(\frac{|4000-300|}{1500}\right)^{2.5}}\right]^{-1} \quad (4)$$

Indicators I2 to I16 have different values for these five parameters, which define their value functions shapes as DL, ICcv, ICvx, or S-shape. Table 6 presents these parameters and value functions for each indicator. The researchers defined these parameters based on technical literature and experts' knowledge. In this definition, for instance, the researchers considered to make the indicator crucial and mainly consider full contributions using an ICcv shape. Or to promote the indicator as it was a new implementation and, therefore, positively evaluate all the small contributions of each alternative using ICvx or DCvx functions.

Sustainability indexes

This step determines the sustainability for the alternatives. Table 7 lists the main architectural, technical and environmental features for the five alternatives based on developed requirements tree. Table 7 took into account the boundaries in this research project (Section 3). For instance, the economic values for all alternatives are the required costs to develop each one for 200 m^2 façade for one of the case studies. Therefore, this table considers Spanish contexts and sources to calculate all values, from energy consumption to emission rates, as Appendix G explains in detail. All values, due to the novelty of these IFL, have been obtained through various communications, databases and literature reviews as presented in references column. For example, values for indicators 1 to 6 – manufacture, labor, transportation and assembly costs – calculated using BEDEC database [116], Ubakus [117], European Environmental Agency [118] and other resources.

This step generates the global sustainability index for each alternative GS_k and then their partial indexes for their economic, environmental, and social requirements $SI_{R1,k}$, $SI_{R2,k}$, and $SI_{R3,k}$ respectively. The global sustainability index GS_k for the five defined IFL alternatives is presented in Table 8 along with the partial satisfaction indexes for the economic, environmental, and social requirements (SI_{R1k}, SI_{R2k}, and SI_{R3k}).

Most sustainable IFL alternatives

This part selects the most sustainable alternative, as well as the most appropriate IFL technology, which has the highest economic, environmental and social indexes.

As shown in Table 8, the indexes show that the most sustainable alternatives with maximum global index are "A4 Kinetic PTFE Mashrabiya" and "A5 TiO_2 covered thermoformed tiles". The main strength to implement A4 IFL is its capability to provide both maximum thermal and visual comfort with its automatic dynamic translucent blinds. A4 also has the highest satisfaction for blocked embodied carbon assessment because of the moving patterns of this system. This index for the alternative A5 is also high because it could improve air quality and olfactory comfort, and considerably reduce pollution concentration. The design of these tiles, along with novel paint, can secure a sufficient airflow in classrooms to enhance comfort. Moreover, this alternative has the lowest environmental impact during all LCA phases due to its high reusability and recyclability rate. However, it has a small influence on the energy consumption by the building. In the case of "A2 Bioreactor panels", their green color makes an innovative approach by providing privacy, shading and a greenery view. These IFL can also be implemented on all kinds of building types. A2 has the best performance in terms of energy-saving and energy conversion efficiency. The concept in which biomass is integrated into the façade is quite new and this issue placed this layer as a most costly alternative in manufacture, maintenance, and dismantling phases. However, in the normal production of electricity, biomass is the second biggest renewable energy source. This technology has high production and maintenance costs because it requires numerous equipment such as a heat exchanger, an algae separator and a receiving tank (see Appendix F.2). This complicated equipment also gives A2 and "A1 ETFE inflating cushion" the lowest indexes for ease in assembling indicator. Considering the assembling process for these technologies, alternatives "A3 Ever-changing PC show", A4 and A5 are considerably simple. On the other hand, flexibility indicator results show that A4, which is connected and operating with a computer-controlled system, does not provide absolute comfort for users.

As concluded from panel members' inputs, the reusability of a technology and material is more valuable than its recyclability and panelists preferred systems that they can dismantle and install for other projects. According to Table 7, all systems are almost completely recyclable. In the case of reusability, 80% of the alternative A3 can be reused for other construction projects due to the design of its components (see Appendix F.3).

Discussion

The previous results prove that the application of this new model based on MIVES and Delphi was successful and resulted in satisfactory values and sustainability indexes for the five alternatives considering the updated economic, environmental and social regulations.

From the application point of view, the experts highlighted the strength this new model has to help unexperienced administrators when deciding the optimized IFL technology to employ for school buildings and to become aware of the importance to incorporate active methodologies. All the direct applications should be related to the assessed alternatives and be in line with the boundaries, requirements tree and value functions this assessment model has [80].

The obtained global sustainability indexes depicted in Table 8 show that for this specific case study of public primary schools, the kinetic PTFE Mashrabiya layer and the TiO_2 covered thermoformed tiles have the best economic indexes during LCC analysis, with an average value of 0.68. While others also have the best environmental and social indexes. The most environmentally friendly alternative incorporates energy generation system with lowest impacts in LCA analysis. Regarding social requirements, which are the most important for this research project, the best solutions are those that provide maximum safety and comfort. However, from the resulting low indexes, we conclude that all these five alternatives need optimization in most indicators before being applicable as IFL in refurbishment projects on schools façades. This is especially the case for economic indicators that, as expected, are not acceptable for these case studies and must be optimized.

Therefore, in order to improve on these alternatives in this study case, the most effective action would be improving their developing and assembling processes.

Sensitivity analysis

Finally, in this last phase the robustness of the results is discussed by applying sensitivity analyses considering three probabilistic scenarios as

Table 9
Variable scenarios used for sensitivity analyses.

Sustainability requirement	Panelist scenario (E1)	Neutral scenario (E2)	Economically biased scenario (E3)	Environmentally biased scenario (E4)
Economic	34%	33.33%	50%	30%
Environmental	36%	33.33%	30%	50%
Social	30%	33.33%	20%	20%

Table 10
Sensitivity analyses and variations for each scenario from research project scenario.

Variation E1 to E2	Variation E1 to E3	Variation E1 to E4
0%	1%	0%
1%	−5%	2%
0%	−2%	1%
1%	5%	−3%
0%	9%	0%

shown in Table 9. These analyses were used to test the robustness of this new model and analyze alternatives' most paramount capabilities in sustainability themes. In this sense, all alternatives are assessed through changing the assigned weights for requirements. This step studies the influence in four different scenarios on the prioritization of the aforementioned alternatives' global sustainability indexes [42].

As shown in Table 9, scenario E1 corresponds to the economic, environmental and social weights originally proposed by the panelists in Step 4 of first phase. Alternatively, scenario E2 considers a balanced distribution of weights, in which the requirements have the same weight. In scenario E3, the final decision has been obtained with the greater weight placed on the economic requirement and finally, in scenario E4, the environmental requirement was assigned a greater weight. Finally, the robustness of this study is achieved when each requirement for each scenario in all alternatives does not have a variation more than ±10% from this research project panelists' scenario.

Table 10 shows the results of these sensitivity analyses. These analyses, in all scenarios, reinforce the previously obtained results in section 4.5 showing that alternative A4 performs better than other alternatives. The GS_k of other alternatives changed in the ranking above or below. A2 changes from third position in the scenario E3 (in which the economic requirement has a major weight), to the fourth position while the other investments underwent insignificant changes. However, these changes are not significant and confirm the robustness for the approach used in this research project.

Commentary

The application of this new model along with the carried-out sensitivity analyses resulted in robust global and partial satisfaction indexes that coincide in defining the best IFL for public primary schools as low-cost and capable to provide maximum light and thermal comfort. The previously mentioned technical literature shows how these points positively influence pupils' comfort and academic performance. However, detailed thermal comfort and academic performance analysis would be necessary to determine the extent of these improvements.

The present model is adaptable to the particularities of other contexts, for example other areas or countries where applicable. This adaptation requires some specific adjustments, for instance the following changes:

a. In step 1, the limitations, exclusions and inclusions must be updated depending on the specific context, problem, in which the study is developed as well as its economic, environmental and social regulations.
b. In step 4, weight assignment must be reliable and objective; based on scientific-technical reasons and panel specialists' feedback.
c. In step 5, value functions should be adapted based on the updated boundaries for the first step.

This innovative model has also found that the alternatives with the least energy demand and maximum efficiency are more preferable. Because these alternatives reduce or eliminate the energy demand for IFL operation, as well as being able to generate energy for heating, cooling, ventilation, and lighting. As mentioned, this capability is called energy conversion efficiency; which analyses show that this ratio needs to be positive even in small-scale refurbishment projects. These indexes also show that an optimized IFL alternative for the case study should fulfill the following:

1. Be responsive to indoor and outdoor environment changes.
2. Incorporate renewable energy systems and be able to supply energy for its own operation.
3. Control the loss and the gains of thermal energy during heating times with its insulation and airtightness.
4. Provide secure, healthy and comfortable inner classroom conditions for pupils' learning processes.
5. Provide an optimal visual comfort adjusted to conditions in a classroom and permit natural light to enter as well as stop undesired solar radiations.
6. Provide an optimal olfactory comfort, reduce pollution concentration and permit natural ventilation
7. Be adjustable and modifiable according to users' requirements.
8. Be able to incorporate reusable low-cost materials in order to reduce the production cost and increase environmental indicators satisfaction.
9. Be able to reuse the constituent technologies during their end of life phase.
10. Be as simple as possible in order to incorporate members of a school community during its assembling process.
11. Develop with maximum safety considerations that do not pose any danger to pupils.

Conclusion

The main novelties of this research article are the definition of an innovative MIVES-Delphi assessment model able to quantify the sustainability for IFLs and its successful application to optimize their function and installation in existing public schools. This new model is rigorous, multidisciplinary and holistic by being based on seminars where experts participated and used value functions to integrate all the different indicators considered. This has been done by considering three requirements, six criteria and sixteen indicators. The use of this model relies upon previous successful applications at the professional level in other fields of expertise. These methods permitted the researchers to include most qualified experts and most reliable data with minimum biases, incorporate main indicators from energy efficiency to social values, generate the most appropriate alternatives, select the most sustainable alternatives and finally propose recommendations to develop optimized IFL alternatives with the highest sustainability indexes. In addition, this model supports an interdisciplinary connection among different fields of knowledge in IFL technologies and provides researchers with a new attitude that incorporates the vision of all actors involved: school administrators, pedagogues, students, façade developers, environmental specialists, waste managers and construction professionals. This model, with its many features, can help decision makers to choose the best solution for optimizing such façades. In addition, this model enables the comparison of the design alternatives and their prioritization while minimizing the subjectivity in the decision-making process.

In this study, this new model has been applied to assess the theoretical use for five exemplary IFLs to optimize the façades in Barcelona public primary schools. This first application has been used to verify the initial hypothesis in this study.

This application has identified the most sustainable IFLs by quantifying the highest sustainability and partial satisfaction indexes as well as the main components, features and details of these developed technologies. Results assisted the authors to figure out the most feasible technologies. These findings indicate that the best optimized IFLs for Spanish public primary schools' refurbishment must be dynamic, cost-effective, energy efficient, environmentally friendly and provide secure, healthy and comfortable inner classroom conditions. In consequence, this study concludes that optimized IFLs could be used to improve façades on existing schools.

By performing a sensitivity analysis, researchers can conclude that the results described above are robust and changes in the values of both the indicators and the weights assigned yield the same rankings among alternatives.

Future projects

This new model could be applied from now on by school administrators and designers when they decide to optimize their schools' façades for maximum efficiency at minimum costs in Barcelona. This model could also be applied to other samples but such application would require to study the new context and location in order to adjust the model properly.

The results of the present application will be the foundation to propose new IFLs that have the highest sustainability indexes as shown in the present case study. These proposals will probably be a combination of the assessed technologies and aim to provide a wide range of façade refurbishment possibilities for schools' façades in all design and use processes. In this sense future steps in this research study include: develop detailed proposal designs; simulate and analyze their energy consumption, energy performance, emission absorption, optimized comfort, ventilation performance and energy production for the case of Spanish public educational centers; build a realistic prototype for this proposal and carry out detailed thermal comfort and academic performance tests.

In addition, the ongoing review on the related technical literature that started in this article shows that the economic dimension of sustainability in IFLs, which in the specific case of public schools has the greatest impact on decision-making process, requires further research in order to improve the decision-making process in the development of IFLs.

CRediT authorship contribution statement

Saeid Habibi: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft, Visualization. **Oriol Pons Valladares:** Conceptualization, Methodology, Visualization. **Diana Peña:** Conceptualization, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A. Qualifying panelists as experts

Qualified experts must satisfy a minimum three of the following requirements:

- Be the primary or secondary writer of at least three peer-reviewed journal articles.
- Have at least 2 years of professional experience in the field of education and construction and architecture or another related field.
- Be a writer or editor of a book or book chapter on the topic of education and construction and architecture or another related field.
- Possess an advanced degree in the field of civil engineering, education and construction and architecture or another related field.
- Hold the position of designer or developer of façade materials for a construction company.
- Have academic experience in the field of sustainability assessment methodologies.
- Be a faculty member, instructor, educator or pedagogue for an educational center.

B. Flexible Point System

This study chose those panelists who score at least 2 points in four different achievement categories.
Table B.1. Flexible Point System for the Qualification of Expert Panelists

Achievement or experience	Points
Peer reviewed journal	3
Conference papers and presentation	1
Years of experience	1
Member at an accredited educational center	2
Writer/editor of a book	4
MS	2

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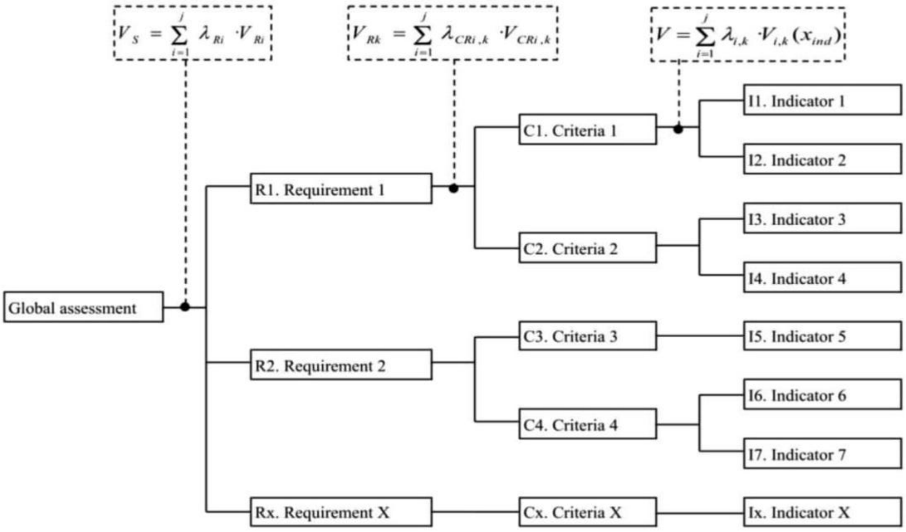

Fig. D1. MIVES generic requirements tree.

(*continued*)

Achievement or experience	Points
Ph.D.	4
Sustainability expert	2
Façade designer and developer	3

C. Controls implemented to decrease bias:

1. Randomize the questions for each panel member during each round of surveys by using a deterministic Random Bit Generator (DRBG) [169].
2. Request a very brief justification from each panelist to his or her responses and report them in the second round to other panelists to control their feedbacks.
3. Conduct questionnaires in different rounds, as needed, in order to reach consensus by reducing variance and bias in responses and improve precision, as supported by pertinent literature.
4. Report the median of the results during the second round rather than the mean.
5. Discard the panelists who had participated in similar events.

D. Theoretical schema of MIVES requirements trees

E. Studied alternatives

Table E.1 shows the broader sample of 21 IFL cases that are the result of a simplified literature review on exemplary IFL. This table has been designed based on previous classification of IFLs in Table 1.

Table E.1. Studied alternatives general features.

N°	NAME	LOCATION	Y	PS	RP	TR	RS	TY	FM
1	Pompeii Fabra Library	Mataró, Spain	1998	IG	F	SR	PV	CP	SM
2	Tourism office	Alès, France	2001	EX	F	TA	PV	CP	SM
3	MIS Museum	Rio de Janeiro	2016	EX	F	TA, L		DSF	S
4	Breathing Skins	Stuttgart	2016	EX	SA	TA, SR		DSF	P
5	Banal building	Jeonlanam, Korea	2017	EX	F	SR, TA, L		CP	WB
6	BIQ house	Hamburg	2013	EX	HY	SR	HT	BF	SM
7	Sidney & Lois Eskenazi Hospital	Sydney	2014	EX	SA	SR		CP	S
8	House of Natural Resources	Zürich	2016	EX	MC	SR	PV	SF	SM
9	Arab World Institute	Paris	1980	IG	MC	L, SR		KF	G
10	CASE	N.Y.	2014	EX	MC	SR, L	PV	SF	SM
11	Hygromorphic skin	Stuttgart	2015	EX	SA	TA		DSF	SM
12	Bloom	Los Angeles	2012	EX	SA	TA, L, SR		DSF	SM
13	One Ocean	Jeollanam-do, South Korea	2012	IG	MC	TA, L		KF	P

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N°	NAME	LOCATION	Y	PS	RP	TR	RS	TY	FM
14	University of Kolding	Kolding, Denmark	2014	EX	MC	LC, SR		KF	S
15	Al Bahr Towers	Abu Dhabi	2012	EX	MC	LC, SR		KF	P
16	Kiefer Technic Showroom	Steiermark, Austria	2007	EX	HY	SR, L		KF	T
17	Media TIC	Barcelona	2009	EX	MC	SR		KF	P
18	King Fahad Library	Riyadh Saudi Arabia	2013	EX	F	SR, L		CP	T
19	The Fluid Glass	Liechtenstein	2012	IG	MC	SR, L,	HT,PV	SF	SM
20	Hospital General Dr. Manuel Gea	Mexico City	2013	EX	SA	AD, L, SR		BF	P
21	Headquarter building	San Francisco	2012	EX	HY	N, L, SR,TA	WG	SF	P

Legend: Y: year; Ps: position; Rsp: Responsiveness; Tr: Treatment; RS: Renewable system; Ty: Type of IFL; Fm: Filling material; External (EX); Integrated (IG); Hybrid (HY); Mechanical (MC); Self-actuate (SA); Fixed (F); Temperature and Air (TA); Light (L) ; Solar Radiation (SR); Wind-Generator (WG); Photovoltaic (PV); Hydro-Thermal (HT); Double skin façade (DSF); Curtain Panels (CP); Kinetic Façade (KF); Bio-Façade (BF); Solar façade (SF); Polymeric (P); Glass (G); Steel (S); Waste-based (WB); Smart material (SM);

F. Brief description of five defined alternatives

As shown in Fig. 2, the defined alternatives are completely independent of the main structure a façade has, which can be dismantled and implemented in another building. The filling materials in these alternatives, as supported by our research project objectives, can be substituted by low-cost materials for Spanish primary schools' use. The applied technologies in these alternatives are quite new and their high efficiency level have been completely proven by professionals.

In the alternative (A1) three layers of the ETFE are fixed within the triangular frame and inflated by Nitrogen-base pneumatic system like a pillow. The resulting bubble contains up to three air chambers that together create a shade-effect and provide thermal insulation for the building. The first layer is transparent, but the second and third layers have a reverse-pattern design which, when inflated or deflated, makes the façade transparent or opaque [60,108,123].

Another source is Biomass (A2), which is quite new in the use as a renewable energy source on the building side, but the potential to generate energy with it in a building's skin is undeniable. Theoretically, it is possible to generate thermal energy with Biomass as well as to produce external electric energy during biomass production [119]. In the center of everything are algae-filled panels and the sun, which provides energy, while the algae can make photosynthesis. Due to photosynthesis, they multiply and produce biomass. This biomass goes into a biomass reactor in order to produce biogas. This biogas will burn in a fuel cell in order to produce electricity. This burning in a fuel cell produces heat and CO_2. Heat is fed into a power station and CO_2 into the panels. On the other hand, while absorbing sun energy, the algae heat up and feed into the power station. The saved heat in the power station can be used to heat the building or for water use [66,120]. Furthermore, Kinetic technologies can be integrated into the skin of a building in the form of a layer around the building. These layers can be used for insulation, light and solar control and privacy of views. In two alternatives, the shifting of the layer's configuration is completed by means of actuators and pneumatic systems.

Only a few examples exist worldwide that use the wind in the production of electric energy in a building's skin, but wind offers diverse possibilities and has a high potential [170]. While wind operates the turbines, a lattice of thousands of five-inch-square, clear-polycarbonate panels, which are hung, are also freely moving (A3)[67]. During the day, these hung tiles providing an undulating show of waves for the inhabitants. At night, this movement is converted into light [162]. As the wind presses the hung panels inward, and a small-embedded magnet connected to an electrical reed switching LED lights on. Moreover, water as a source of renewable energy provides a plurality of possibilities if we think about waves, tides or hydrogen power. For generating energy in the façade, the heat storage potential and the heat exchange potential of water in combination with being warming up by the sun is most interesting [68,69].

The other one (A4) is a traditional Arab latticework coated with polytetrafluoroethylene and programmed to respond to the movement of the sun during each day of the year. In the evening, all these screens will close. At night, they will all fold, so you'll see more of the facade. The area covered by PTFE in each tower is 1840 m^2 and composed by 1049 panels [63,70].

The alternative (A5) however is not active, but it is intelligent enough. The Berlin-based design firm Elegant Embellishments designed this layer to fight against smog. This layer is covered by a titanium dioxide-based pigment, which can neutralize the smog produced by 8,750 cars every day [72,73].

According to the designers, when ultraviolet rays from sunlight reach the titanium dioxide on the tiles, they trigger a chemical reaction and smog breaks down into safer chemicals, such as water, carbon dioxide, and calcium nitrate. In addition, the innovative design of the panel shapes, slows wind speed and creates turbulence, for better distribution of pollutants across the surface, and circulates naturalized air to the users. Consequently, the renewable energy sources, in the form of wind, fluid, biomass, and air, plus passive intelligent materials, are interesting for the technical system in a sustainable producing façade [64].

The following illustrates the main constituents to develop each alternative in their developed edifices mentioned in Table 7.

F.1. Alternative A1 (ETFE inflating cushion)

Total cladding area, which is 1660 m^2 with a total assembling time of 12 months.

Table F.1. The main components of Alternative A1 (Media TIC building façade) [123].

No.	Reasoning	Material	Shape	Dimensions	Unit
1	3 layered air chambers	ETFE 0.35 kg/m^2	–	Upper: 200 μm, Middle: 100 μm, Lower: 200 μm	135
2	Frame	Aluminum	Tube	(4 × 4 cm) × 3 + 3 + 3 *m*	135
3	Vertical main columns	SS 1.4462 duplex	Tube	(0.5 × 0.5 m) × 37.8 *m*	3
4	Horizontal beams	SS 1.4462 duplex	Tube	(0.25 × 0.25 m) × 44 *m*	8.25
5	Horizontal connecting beams to building	SS 1.4462 duplex	Tube	(0.2 × 0.3 m) ×4 *m*	30
6	diagonal connecting beams to building	SS 1.4462 duplex	Tube	(0.27 m diameter) × 4.5 *m*	10

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No.	Reasoning	Material	Shape	Dimensions	Unit
7	Flooring horizontal beams	SS 1.4462 duplex	Tube	(0.2 × 0.3 m) × 44 *m*	2 × 4
8	Flooring horizontal beams	SS 1.4462 duplex	I shape	(0.1 × 0.15) × 4.5 *m*	2 × 30
9	Horizontal structure for the diaphragms	SS 1.4462 duplex	Tube	(0.14 m diameter) × 44 *m*	10 floors
10	Vertical structures for the diaphragms	SS 1.4462 duplex	Tube	(0.14 m diameter) × 3 *m*	210
11	Nitrogen pneumatic mechanisms	–	–	200–600 Pa	1
12	Energy free sensors	–	–	–	104

F.2. Alternative A2 (Bioreactor panels)

Producing 6487kwh/year with 70% efficiency for 2152 square feet and around 1000kwh energy consumption per year.
Each panel is 70 cm wide, 270 cm high and 8 cm thick.
Each panel volume is ~24 l = 0.024 m^3 and weight is ~300 kg.
The total assembling and calibration time is 2 months for all the 200 square meter of façade layer.
Table F.2. The main components of Alternative A2 (BIQ house).

No.	Reasoning	Material	Shape	Dimensions	Unit
1	Main connecting structure to building	SS 1.4462 duplex	–	0.5 *m*	2 unit/panel
2	Main structure	SS 1.4462 duplex	U-shape	0.7 *m*	2 unit up and down
3	Panel Frame	aluminum	Rectangular Tube		6.8 m/panel
4	Glass tile	Glass	Flat	2.7 × 0.7 × 0.06	2 /panel
5	Do sensor	–	–	–	1
6	PH sensor	–	–	–	1
7	Temperature sensor	–	–	–	1
8	Inlet tube	Stainless steel	Pipe	–	1
9	Outlet tube	Stainless steel	Pipe	–	1
10	Heat exchanger	–	–	–	1
	Algae separator	–	–	–	1
	Conversion equipment	–	–	–	1
	Addition and removal of culture medium	–	Pipe	25 mm diameter	1
	Tank	–	–	–	1

F.3. Alternative A3 (Ever-changing PC show)

Total 60 days assembling time.
Total layer area 98.10 m^2.
Table F.3. The main components of Alternative A3 (SFPUC San Francisco) [69,124,145].

No.	**Reasoning**	**Material**	**Shape**	**dimensions**	**Unit**
1	panel	Polycarbonate	Square	5.6 × 5.6 cm	15,480
2	Horizontal profiles to hang panels	Aluminum	Square tube 1x1 cm	4.2 *m*	344
3	LED light	–	–	–	15,480
4	Vertical glass frames	Aluminum	Tube	23 *m*	12
5	Horizontal glass frames	Aluminum	Tube	6.9 *m*	15
6	Glass panels	Glass	–	–	–
7	Vertical Structure	Stainless steel	Tube	23 *m*	5
8	Horizontal structure	Stainless steel	Tube	11.35	15
9	Flooring	Galvanize	–	1.89 m^2	15
10	Main connecting structure to building	Stainless steel	Tube	28.92 *m*	4
11	Flooring	Galvanize	–	4.2 m × 3 *m*	4

F.4. Alternative A4 (Kinetic PTFE Mashrabiya layer)

Total 12 months to assemble and install all components, and 3 to 6 months for software calibration and commissioning.
Each panel: 4.2 × 4.5 m = 520 kg
Table F.4. The main components of Alternative A4 (Albahar tower) [63].

No.	Reasoning	Material	Shape	Dimensions	Unit
1	Connects to main structure	SS 1.4462 duplex	Strut-Bracket	2 *m*	1/panel
2	Supports the whole mechanism	SS 1.4462 duplex	Y-frame	8.2 *m*	1/panel
3	Relieves the actuator shear forces	SS 1.4462 duplex bar	Stabilizer	4.5 *m*	1/panel
4	Frame	Aluminum	Rectangle tube	39 *m*	1/panel
5	Infill material	Fabric Mesh	–	9.45 m^2	1/panel
6	Linear actuator	–	–	1000 lb	1/panel

F.5. Alternative A5 (TiO_2 covered thermoformed tiles)

Total façade area is about 17 × 140 m = 2500 m^2 with the total assembling time of 4 months
Table F.5. The main components of Alternative A5 (Hospital General Dr. Manuel Gea).

No.	Reasoning	Material	Shape	dimensions	Unit
1	Tile	Thermoformed plastic	–	0.49 kg/m^2	510 blocks
2	Horizontal structure	Stainless steel	Tube	140 *m*	6
3	vertical structure	Stainless steel	Tube	17 *m*	70
4	Finishing	TiO_2 Disperlith Primer	–	–	6–8 m^2/ltr

G. The main considerations for calculating values

The following are the main considerations for the calculation of each value in Table 7.

1- The values for indicators I1 to I13, have been analyzed based on the Effect Estimate of components of each alternative.
2- The cost and energy of crane needed for construction is also calculated for the indicators I1 to I6. The crane has a 30 m turning radius jib, with 40 m high, 2 t tip weight and energy efficiency of 70%.
3- For Indicator 1, the cost of the zero phase was not considered. In addition, the cost for onsite engineers was also not considered.
4- The cost and energy of transportation is also included in the values for indicators I1 to I6. The considered transportation truck is a Class-7 Local delivery trucks [0.08 Gal/km] [33.7kwh/gal] [box = 2.14x5.13x2 = 2040 kg] [capacity = 9312 kg = $21.9m^{3out}$ = $20.3m^{3inner}$].
5- The cost and energy used for packing for alternatives I1, I5, and I6 was not considered.
6- The values for indicators I6 and I9 are US ton units.
7- The values for emissions, for some cases which there was no valid reference, is calculated based on the reference emission rate in Spain per Kwh, which is $679gco_2$/kwh [102].
8- For all price's values, a 2% auxiliary expense on labor is also added.
9- The total amount of aluminum and stainless steel used is calculated by easy-calc.com [107]
10- The values for cost and energy for crane, transportation and labor are calculated based on 8 h work per each day.
11- The considerable part of value for energy saving indicators has been calculated based on the U-value for each alternative which is analyzed and extracted in www.ubakus.de [117].

H. The abbreviations used in the text

Table H.1. The abbreviations used in the text.

Abbreviations	Relevant values
GHG	Greenhouse Gases
HVAC	Heating, Ventilation, and Air Conditioning
IFL	Intelligent Façade Layer
nZEB	Nearly Zero-Energy Buildings
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MIVES	Integrated Value Model for Sustainable Assessment (Modelo Integrado de Valor para una Evaluación Sostenible)
MCDM	Multi-Criteria Decision Making
AHP	Analytic Hierarchy Process
PTFE	Polytetrafluoroethylene
ETFE	Ethylene Tetrafluoroethylene
PC	Polycarbonate
DO Sensor	Dissolved Oxygen Sensor
TiO_2	Titanium Dioxide
SS	Stainless Steel
DSF	Double Skin Facade
Kwh	Kilowatt hour

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Chapter 5.
Monitoring & Optimization

This chapter analyses the feasibility of employing household waste materials in educational workshops for developing façade alternatives, by applying pioneering experimental campaigns on the degradation behavior of waste materials and their mechanical properties.

This chapter results have been published in **Article D** of this research thesis with the title *"Evaluation of household waste materials for façade components in primary educational workshops. Degradation behaviour and mechanical properties of aged samples"*.

5.1. Introduction

During the previous chapters, the potential of extensive IF technologies as a sustainable constructive system over traditional façade solutions in urban areas is consolidated. However, the previous chapters highlighted the importance of replacing materials used in different layers of these systems with more environment-friendly and sustainable products. This proposal of replacement aims to reduce their final production costs, embodied energy, and embodied carbon.

Early evidence on the circular economy model, values MSW as a zero-cost resource that can be reused as modifiers composition of construction materials [102]. In addition to its economic advantages, reusing waste in construction can also contribute to reducing environmental impacts. Waste reusing has social benefits for considered society as well [103].

Most MSW materials are low-degradable, which is considered an advantage during the new circular economy models in terms of high durability [104]. Nevertheless, to seriously introduce household waste materials as a construction material in architecture, the professionals involved need to understand the properties of these materials in depth.

To the candidate's best knowledge, the degradation behavior of these materials needs to achieve durability of one year in the case of waste-based IFs applicable to the case study. This durability period relies on reviewing previously carried out studies. This chapter responds to this need by carrying out a new mechanical and aging experimental campaign for aged MSW and comparing the obtained results with a former study. The former study had been carried out by candidate supervisor research team which reported the same campaigns on the new MSW samples.

The tests focus on exterior environments, and samples were subjected to both laboratory and natural environment aging. These samples were 7 reusable waste materials as HDPE bottles, PET bottles, PS yogurt cups, Tetra brick packages, PE film bags, cardboard, and paperboard. This campaign also studied the following seven novel solutions: polyamide threat, brass eyelets, stainless steel bolts, copper wire staples, water-based white wood glue, solvent-free universal transparent glue, and transparent hot melt adhesive. Finally, to finish the surfaces of the mentioned items, 3 groups of products are analyzed as follows: 1) acrylic paint + varnishing, 2) poster paint + varnishing, and 3) TiO_2 paint.

In this chapter by considering the specific durability requirements of the developed IF solutions and utility model in previous chapters, 41 test samples have been generated; had been analyzed in the laboratory through a set of natural weather aging test campaigns. Fifteen other test samples had been analyzed through mechanical test campaigns during the years 2017 to 2020.

The first test sample type, tests A01 to A19, followed ISO 4892-1:2016 and ISO 4892-2:2013 in the laboratory. While the second type, tests A20 to A41, consisted of exposing samples to natural weather conditions in a representative location of this research case studies. There were three locations and durations of real weather tests including a) in the neutral location "NL" during 500 hours, b) in NL during the 12 months, and c) in the case of studies location also during the 12 months project durability.

The third test sample type, tests Ma01 to Ma15, were mechanical tests on aged samples. In order to determine the maximum tensile load and tensile properties in accordance with ISO 527 (ISO, 2012).

these tests area have been carried out at room temperature using universal testing equipment with a 1 kN load cell and a video extensometer to measure the strain.

The resulting degradation from the laboratory aging tests consisted of a) the separation of sheets in 11 types of sample sets; b) increase of stiffness, swelling, distortion, and/or yellowing of the base material in 15 sample types; c) darkened, bluish and/or corrosion of joints in nine types and d) delamination, cracked surfaces, painting losses, brightness changes and/ or yellowed surfaces of the finishing in 9 sample types.

The following types of degradation have been involved in the natural weather aging test: a) sheet separation in 11 types of sample sets; b) stiffness increase, swelling, distortion, and yellowing of the base material in 14 sample types; c) red corroded or unfixed joints in 6 types; d) painting losses and/or brightened finishing surfaces in 5 sample types and e) green growth dying in the green curtain case.

The results of the mechanical tests on aged samples, namely maximum tensile load and maximum shear load, showed relatively lower average load in most cases. The test Ma01 (aged polyamide threat) emerged as the one with the best mechanical performance of all tested samples considering the average load of 769 N. Regarding the main aged joint (J2p) that consisted of Tp knotted to two bottle caps inserted in an aluminum profile, its strength drops to 613 N. The tensile strength of C04 (Tb), C05 (HDPE), and C06 (PET) has been reduced by 46%, 19%, and 9%, respectively. The strength of other joints has been decreased even further.

5.3. Contribution to thesis

This chapter carried out the experimental campaign with the following contributions to the thesis: a) check the feasibility to employ household waste during the workshops of this research project, b) obtain values to prepare design guidelines for the workshops, and c) obtain values to analyze these façades using finite elements software tools.

Accordingly, this chapter explored the exterior weather-resistant waste containers and elements with minimum stiffness loss, yellowing or distortion, and maximum tensile properties. The mechanical properties of aged Tetra Pak have been reported for the first time to the best of the candidates' knowledge. As expected, the tensile strength of the used materials composed of HPDE, PET, and Tetra Pak has decreased due to UV aging. However, all identified materials and components as well as the main joints and stapled joints, are exclusively applicable to the case study and workshops and fulfill the project durability norms. However, a specific alternative of PET bottle-based plant pots appeared not to be an acceptable design because the greenery has not grown properly. Moreover, this chapter successfully introduced TiO_2-based finishing as the only applicable finishing with minimum paint losses and brightness.

5.3. Contribution from the candidate

The experimental test, data treatment, and analysis of the tests were the main tasks of the candidate to explore the MSW experimental set-up. The candidate led the development of, various test samples of waste items, with more than 41 different test specimens, with different characteristics and their long-term and short-term experimental campaigns. Worth to mention that all toxic, allergic, and unsafe waste items have been screened by the candidate. The candidate after analyzing previous reports approved that there are no similar reports on the degradation and mechanical properties of mentioned defined specimens.

The candidate collected, prepared, and classified all test specimens for this campaign as primary joints, secondary joints, elements, and devices. The candidate communicated with potential TiO_2 producers in Spain and provided data sheets and their application manuals and safety considerations. Later on, the candidate supervised and reported the shower hours, water spray cycle, irradiations, temperature, and relative humidity in both laboratory and natural weathering tests. Later on, the candidate reported the degradation patterns of all test samples during the test period in both external and laboratory tests. The candidate analyzed, recorded, and reported any swelling, distortion, yellowing corrosion, painting losses, and sample broken in all test specimens. The mentioned reports have been carried out through weekly and monthly attendance of the candidate in the representative sites in different locations of the municipality of Catalunya.

Moreover, the candidate normalized the results of shear, tensile, and thermal tests and finally divided all the test specimens into exterior weather-resistant and not weather-resistant materials. The artwork and the writing of the scientific article were also a task of the candidate.

5.4. Article D

This section presents the published **Article D** of this thesis. This article covers the monitoring phase of this research thesis by carrying out experimental campaigns on the degradation behaviour of waste materials and their mechanical properties.

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Evaluation of household waste materials for façade components in primary educational workshops. Degradation behavior and mechanical properties of aged samples

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ABSTRACT

This article presents a pioneering experimental campaign on waste materials that rigorously tests numerous specimens to study their degradation behavior and the unreported mechanical properties of aged samples. The novel results of these tests, along with the mechanical properties and fire properties which new waste samples obtained from a previous article have are analyzed to check the feasibility of employing these household wastes in educational workshops for the self-construction of façades. Numerous previous studies on plastics degradation have analyzed the tensile strength reduction of polymers that compose the household waste studied in this project. However, no similar research projects on the degradation behavior of unprocessed Tetra Pak containers are reported in the literature. Most former studies were carried out in laboratories while few research projects studied waste degradation under real environmental conditions. The main results are: finding the unreported Tetra Pak mechanical properties of aged samples, discarding polystyrene household waste and some glues for exterior applications, and succeeding in introducing a TiO2-based finishing for Tetra Pak elements.

1. Introduction

Among the different human global environmental problems [1] there is the high amount of waste generation, its difficult management, low recycling rate versus its elevated dumping percentages and its serious consequences [2]. These problems which debris present at the end of service life coexist within the obsolete linear economy model that considers waste as an undesired product. In consequence, the low degradability of most waste materials becomes a problem [3], and single use waste containers are the worst example because their durability is much longer than the usage period for which humans use them. On the other hand, the rising circular economy model values this waste as a resource for a new cycle [4]. In consequence, this slow degradation process of debris becomes an advantage in terms of high durability during this new debris reuse cycle. The reuse of waste occurs at present in numerous fields as recommended by circular economy policies that urge closing the material use loop by utilizing 'wastes' for suitable applications [5]. The building sector is developing and applying numerous new waste-based construction materials that result from a second production processing cycle [6–10]. Nevertheless, in order to seriously introduce household waste materials as a construction material in architecture, the professionals involved need to understand the properties of these materials in depth.

In this sense, this project studies these properties in the case of waste-based alternatives applicable to the case study: façade components designed and built during elementary education workshops to achieve a durability of one year [11]. These components are solar control devices that have been developed to minimize overheating problems in classrooms during hot seasons and increase pupils' thermal and lighting comfort levels. This required durability responds to the 1-year duration for these workshops, the educational objectives of which are fulfilled after completing 8 sessions during one academic course. This relatively short service life is not common at present in the construction sector, where a durability of 10 years for nonstructural parts such as façades is typical [12]. After this year, the sunscreens' materials will be reused in the next workshop if they maintain the required properties or otherwise recycled by a second processing cycle. These household waste candidates follow the utility model U201831204 [13] while toxic, allergic and unsafe materials are beyond the boundaries of this project [14]. This study takes into consideration previous social initiatives such as

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Do-it-Yourself (DIY) [15–17] that normally focus on the direct use of household waste materials, which is the debris part generated from everyday house activity [18]. This occurs because a great part of household waste satisfies non-toxicity and low allergic requirements that are compulsory in most social workshops, which contribute to reduce waste as well as increasing environmental awareness that is a crucial strategy in the management of waste in a community [19,20].

A previous article within this project tested the mechanical and fire behavior of potential household waste-based façade candidates, achieving interesting and novel results while concluding that the degradation behavior of these materials needed to be studied [21]. This present article responds to this need by carrying out aging and mechanical tests with the following three objectives: a) check the feasibility to employ this household waste in these workshops, b) obtain values to prepare design guidelines for these workshops and c) obtain values to analyze these façades using finite elements software tools [22]. The article at hand focuses on the applicability point of view for this waste as façade elements and does not study in depth the chemical processes taking place during the aging process of these materials. This new experimental campaign takes into account the previously obtained results that exclusively studied new materials [21] and compares these former results to the new results of aged samples reported for the first time in this work.

In this sense, this article first determines the required properties to be studied and then defines test samples to find the unreported values. These identified properties are those that will permit researchers to achieve the previously mentioned three objectives within the case study. Therefore, these properties will fulfill: a) the general requirements for façade elements installed in urban buildings up to 8 storeys high and b) the specific requirements for the new solar control devices defined in the aforementioned utility model. These properties are: tensile, flexural, shear and degradation. The tests carried out to obtain these properties focus on exterior environments, where the most efficient solar control devices are installed [23,24], except one contrast test on an interior inhabited environment. The studied samples were subjected to both laboratory and natural environment aging. The same reused household waste materials as in the previous article were studied, which were mainly plastic materials. Namely, high density polyethylene (HDPE – Table A.1 in Appendix A presents a complete list of abbreviations), polyethylene terephthalate (PET), polystyrene (PS), polyamide (PA) and containers called "tetra briks" (brand name, Tetra Pak, referred to as "Tb") were analyzed. Tb is a composite that is comprised of six layers of paper, low density polyethylene and aluminum [25]. This present study also analyzes other household waste, complementary joining and finishing materials, and three solar control devices which are explained in depth in the following section.

There are numerous previous studies on plastics degradation, which is classified between chemical, physicochemical – including mechanical, photo and thermal – and biological degradation processes [26]. In this sense, many research projects have studied the photo-thermal [27] and biological [28] degradation of plastics. Some of these research papers focus on compostable plastics [29], polyester polyurethane [30], polypropylene (PP) [31], polyethylene (PE) food plastic bags [32], high-density polyethylene (HDPE) [33], PET [34], PS [35] and Polystyrene-graft-starch copolymers [36], among others. Some of these studies have analyzed the tensile strength reduction of these materials in these degradation processes [28,37,38]. To the best of the authors' knowledge, no similar research projects on Tb containers are reported in literature, neither on their properties nor on their degradation behavior in a natural environment. However, there are studies on the degradation of composite materials composed by these Tetra Pak containers [39] after a second processing cycle, which is out of the scope of this research project as previously explained. It was found that Tetra Pak decomposition and delamination occurred during its recycling processes [40–42]. Most of these studies were carried out in laboratories that reproduce different environments such as marine water [43], soil [44] and solar radiation [45] among others. Few research projects studied waste degradation under real environmental conditions. For example, studies on plastic films from olefin polymers such as PE, HDPE, LDPE and linear low density polyethylene (LLDPE) biological degradation in a soil environment during six months [46] and abiotic degradation under natural weathering during 12 months [33,47]. A study of the abiotic and biological degradation processes of: a) HDPE, PET, PVC aged 12 months in a coastal zone [48] and b) PET aged 15 years under the sea [49] has also has been reported. Focusing on reused applications of waste within the construction sector, there are studies on the durability of waste-composed materials. Most of these studies introduce waste in cementitious products for reinforced concrete structures and heavyweight façades [50,51]. However, there are few projects of lightweight elements for the construction sector composed of waste that have studied their durability. This is the case of the new composite board panels incorporating Tetra Pak waste [52] and the wood-plastic composites for outdoor applications [53].

The next sections present the materials, methods, tests and standards that were employed to study the aging behavior and mechanical properties of these waste-based materials, followed by the results and their analysis in order to obtain the appropriate durable household waste candidates for the workshops. At the end this article concludes with the main results, recommendations and future works.

2. Materials and methods

This section presents the materials studied, samples tested, framework methodology, standards applied and tests performed carried out in this research project to determine the aging behavior and mechanical properties required to fulfill the aforementioned objectives.

2.1. Materials

This experimental campaign studies the waste-based façade alternatives described in the utility model ES 1224335 U [13] and previous research steps [14], which are different designs of tensed solar control devices. It follows the findings of a previous research paper [21] that focused on the mechanical and fire behavior of these façade solutions. The components of this utility model are classified in joints and elements. Joints can be primary – for example to fix the device to the window frame – or secondary joints that interconnect elements. These elements are geometrical patterns and volumes made from household waste containers.

From all the possible components of these waste-based façade alternatives, this article focuses on the most adequate and applied alternatives in the workshops carried out until now [11]. To that end, this study analyzes the following seven waste items: 1) HDPE bottles with a wall thickness of 0.6 mm; 2) PET bottles with a wall thickness of 0.2 mm; 3) PS yogurt cups with a wall thickness of 0.2 mm, 4) Tb packages with a wall thickness of 0.4 mm, 5) PE film bags with a thickness of 0.07 mm, 6) 2.3 mm thick cardboard and 7) 0.2 mm thick paperboard. This campaign also studies the following seven joining solutions between waste items: 1) polyamide threat (referred to as "Tp") with a diameter of 2.3 mm, 2) brass eyelets with an internal hole of 4 mm diameter, 3) Ø 3 mm stainless steel bolts with self-locking nuts, 4) copper wire staples size 22/6 [54], 5) water-based white wood glue composed of polyvinyl acetate adhesive, 6) solvent free universal transparent glue composed of polyurethane and 7) transparent hot melt adhesive (HMA) made of thermoplastic resins. Finally, to finish the surfaces of the previously mentioned items, six groups of products are analyzed as follows: 1) acrylic paint + varnishing (Apv), 2) poster paint + varnishing (Ppv), 3) TiO_2 paint type "1" with surface preparation type "a" (Ti1a), 4) TiO_2 paint type "1" with surface preparation type "b" (Ti1b), 5) TiO_2 paint type "2" with surface preparation type "a" (Ti2a), 6) TiO_2 paint type "2" with surface preparation type "b" (Ti2b). The TiO_2 paint type "1" was a water-based dispersion with modified acrylate copolymers [55] with or without powder ink [56], the TiO_2 paint type "2" was waterborne base on vinyl acetate and ethylene modified copolymers [57] with or without powder ink [56]. The surface preparation type "a" was on the Tb aluminum surface with a priming [58] before painting and the surface preparation type "b" was as type "a" but sanding the surface before applying the primer. Paints had four simple colors: true red, canary yellow, blue and grass green numbers 27, 7, 9 and 13 from Tinting-Concentrates Color Card by MIXOL [59].

This experimental campaign studies these waste items, joining solutions and finishing products by means of testing containers, joints, elements and device specimens. Containers are samples of the above-mentioned seven waste items – HDPE bottles, PET bottles, PS yogurt cups, Tb, PE film, cardboard and paperboard – the contents of which had been previously consumed and then these items have been adequately decontaminated (Table B.1, Appendix B). This decontaminating process is crucial to avoid organic growth, bad odors, etc., as well as permitting the ideal performance of glues and finishing. This unpolluting process is also done during the workshop and consists of cleaning using regular domestic soap and subsequent drying for 24 h. Joint specimens were knots between Tp (J1p), two bottle caps joined with Tp and knots (J2p), PS cup and Tp (J3s), rectangular strips with dimensions of 60 × 20 mm^2 that were cut from the HDPE (J4s) and PET bottles (J5s) and fitted with two eyelets. Likewise, strips with dimensions of 120 × 14 mm^2, 70 × 13 mm^2 and 60 × 16 mm^2 were cut from Tb. Joint specimens J6s to J8s included five strips of Tb, stacked together and joined either with staples (J6s), glued with white wood glue (J7s), or with transparent universal glue (J8s) and also fitted with two eyelets. These samples had two pieces of Tp threaded through the eyelets. Joint specimens J9s consisted of two overlapping Tb sheets joined with a single staple; the joint specimens were tested in three directions. Finally, the other joints J10s to J13s were five Tb strips, stacked and joined together exclusively with staples (J10s), wood glue (J11s), universal glue (J12s), or transparent hot melt adhesive (J13s). Table 1 compiles images of the 13 different types of joint specimens.

Element specimens were two Tb strips of 70 × 13 mm^2 stacked together and joined either with staples (E01 and E02), glued with white wood glue (E03) or with transparent universal glue (E04) and finished with four simple colors which mixed in two different types of acrylic paint and poster paint both with varnishing. E05 to E012 were all single Tb strips with dimensions of 70 × 13 mm^2 prepared with 2 types of previously mentioned surface preparation types Ti1a for (E05), Ti1b for (E06), Ti2a for (E07), and Ti2b for (E08) finished with four simple colors without varnishing; while types Ti1a for (E09), Ti1b for (E10), Ti2a for (E11), and Ti2b for (E12) without powder ink covering. Finally, E13 consisted of four Tb strips of 60 × 10 mm^2 stacked together and joined with staples. A specimen was composed of four E13 bolted in a square shape having a Tb origami shaped on top of them. These 13 element specimens are shown in Table 2.

Device specimens were: three louvres (D01), each one composed of two J2p, J10s, 3 Tb sheets, staples, Ø 3 mm bolt and finished with Apv paint; two exterior green curtains (D02), each composed of 11 D02a and eight D02b, including 2 J2p, J1p and bottle caps (D02a) or 4 J2p, J1p, C06, soil & plants (D02b); and four interior curtains (D03), each one incorporating 10 J2p, 3 Tb sheets, 28 origami Tb elements, staples. Table 3 depicts these device specimens. Table 4 describes these 7 containers, 13 joints, 13 elements and 3 devices along with a description of their components, different finishing, different joints and tested specimens.

2.2. Methods

This experimental campaign carried out aging and mechanical tests. Table 5 shows the main information based on the aging tests while Table B.1 in Appendix B depict images of all specimens before and after testing.

The aging tests were of two main types, laboratory and natural weathering tests which were carried out from 2017 to 2020. Generally, laboratory aging tests studied the specimens which fitted the dimensions of the test chamber. On the other hand, natural weathering tests were generally applied to bigger specimens. Both laboratory and natural aging was carried out on some specimens in order to contrast the results obtained through both types of aging tests. The first type, tests A01 to

Table 1
Joint specimens tested in this experimental campaign.

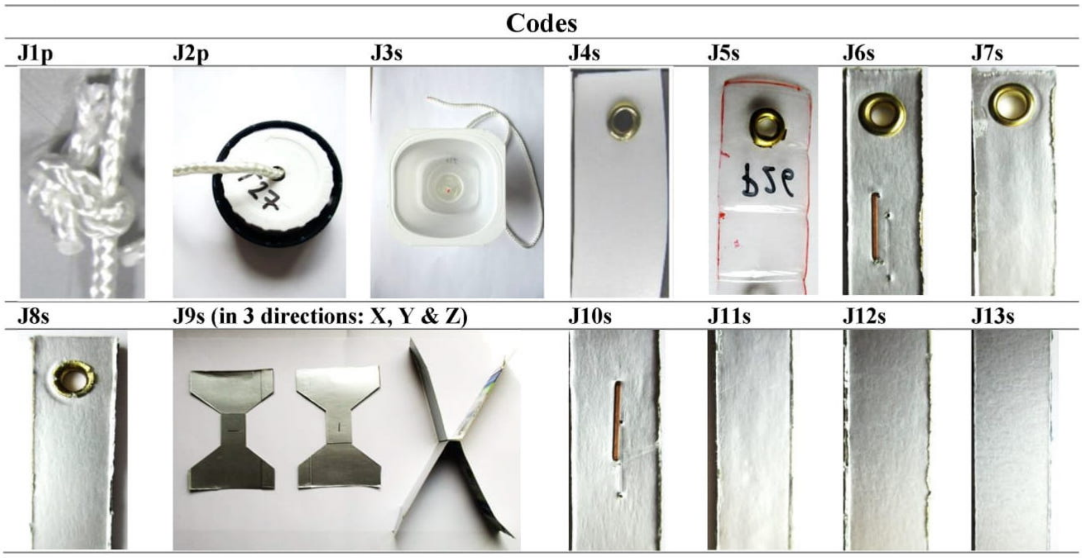


Table 2
Element specimens tested in this experimental campaign.

Codes												
E01	E02	E03	E04	E05	E06	E07	E08	E09	E10	E11	E12	E13

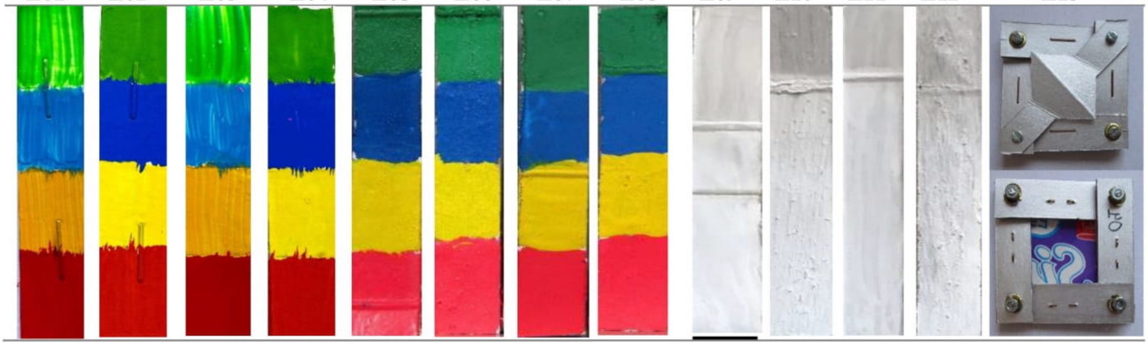
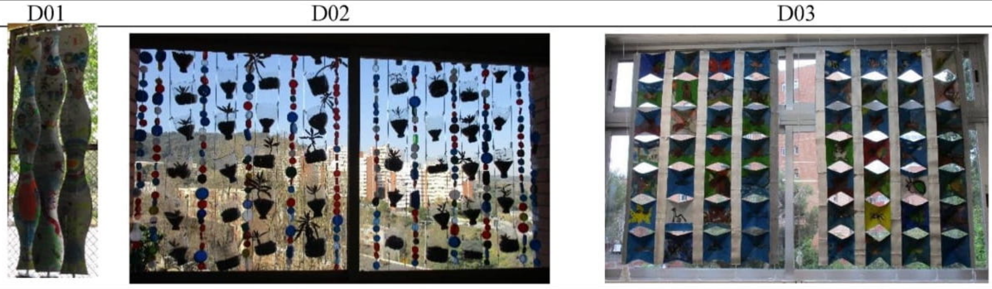


Table 3
Device specimens tested in this experimental campaign.

Codes		
D01	D02	D03



A19, followed ISO 4892-1:2016 and ISO 4892-2:2013 with 500 h of exposition, with a water spray cycle of 18 min and 102 min drying, applying a continuous irradiation of 0.51 W/m^2 ± 0.02 W/m^2 at 340 nm, a Black Standard Temperature during the dry period of 65 °C ± 3 °C, a Cylinder Head Temperature of 65 °C ± 3 °C and a relative humidity during the dry period of 50% ± 5%. The aged samples were analyzed using a visual assessing cabin Gretagmacbeth Spectralight III with D65 illuminant and 45° incident light. The second type, tests A20 to A41, consisted in exposing samples to natural weathering in a representative location of the application of this research project or in the final site and position of these solar control devices. The representative site was within Barcelona metropolitan area, Spain, a Mediterranean region with an annual average radiation dose of 4.6 kWh/m^2 [60,61]. There were three subtypes of real weathering tests. The first subtype - tests A20 to A23 - were in the neutral location "NL" during 500h because these aged samples were going to be tested mechanically afterwards but did not fit in the laboratory chamber. The second subtypes - A24 to A38 - were also carried out in NL but during one year, which is the aforementioned aimed durability of the project. The third subtypes – A39 to A41 - were carried out in their final location and position also during the 12 months project durability. NL was a neutral exterior site not belonging to any school in particular (41°23′03″N 2°06′50″E). The actual locations of the school façades were: Sant Martí school (41°21′0″N 1°58′60″E) for A39, Ferrer i Guàrdia school (41°27′45″N 2°10′32″E) for A40 and Seat school (41°23′30″N 2°6′56″E) for A41. The test dates and main weathering conditions are summarized in Table C1 in Appendix C. As shown in the Appendix, the daily average main conditions of the NL site were: irradiation from 11.40 to 18.37 MJ/m^2, rainfall from 0.02 to 1.86 mm, temperature from 10.8 to 16.3 °C and humidity from 57 to 70%. A39 and A40 were located in vertical west façades, being the most external layer of the openings. In contrast, A41 was the most internal layer of south oriented openings and this aging test was carried out in an interior inhabited environment. The specific conditions of this environment are those of an elementary classroom, fulfilling the Spanish healthiness standards for inhabited buildings in terms of temperature, humidity and air renovation [62].

The mechanical tests on aged samples were carried out following the same standards, using the same equipment and in the same

Table 4
Description of the containers, joints, elements, devices and their specimens.

Code	Type	Components	Specimens
C01	Containers	PE film	Entire containers
C02		Cardboard	
C03		Paperboard	
C04		Tb pack	
C05		HDPE bottle	
C06		PET bottle	
C07		PS container	
J1p	Primary joints	Knots, 2 Tp	
J2p		2 drilled bottle caps, Tp, aluminum guide	J2p with Tp
J3s	Secondary joints	PS yogurt cup, Tp, J1p, bottle cap	J3s
J4s		HDPE sheet, 1 eyelet, Tp, J1p	2 units of J4s together
J5s		PET sheet, 1 eyelet, Tp, J1p	2 units of J5s together
J6s		5 Tb sheets, staples, 1 eyelet, Tp, J1p	2 units of J6s together
J7s		5 Tb sheets, wood glue, 1 eyelet, Tp, J1p	2 units of J7s together
J8s		5 Tb sheets, universal glue, 1 eyelet, Tp, J1p	2 units of J8s together
J9s		2 Tb sheets, 1 staple	J9s in 3 directions
J10s		5 Tb sheets, staples	J10s
J11s		5 Tb sheets, wood glue	J11s
J12s		5 Tb sheets, universal glue	J12s
J13s		5 Tb sheets, transparent HMA	J13s
E01	Elements	2 Tb sheet, 2 staples, Apv	4 colored areas (true red, canary yellow, blue and grass green [49])
E02		2 Tb sheet, 2 staples, Ppv	
E03		2 Tb sheet, wood glue, Apv	
E04		2 Tb sheet, universal glue, Ppv	
E05		1 Tb sheet, Ti1a	4 colored areas (true red, canary yellow, blue and grass green [49])
E06		1 Tb sheet, Ti1b	
E07		1 Tb sheet, Ti2a	
E08		1 Tb sheet, Ti2b	
E09		1 Tb sheet, Ti1a	Without powder ink covering
E10		1 Tb sheet, Ti1b	
E11		1 Tb sheet, Ti2a	
E12		1 Tb sheet, Ti2b	
E13		4 Tb sheet, 1 staple, Ø 3 mm bolts	4 units of E13 & 1 origami Tb sheet
D01	Devices	2 J2p, J10s, 3 Tb sheets, staples, Ø 3 mm bolts, Apv	Three louvres composed of D01
D02		D02a: 2 J2p, J1p, bottle caps	Curtain composed of 11 D02a and 8 D02b
		D02b: 4 J2p, J1p, C06, soil & plants	
D03		10 J2p, 3 Tb sheets, 28 origami Tb elements, staples	Four curtains composed of D03

conditionings of the previous steps of the project that had equally tested new samples [21]. In order to determine maximum tensile load, tensile properties in accordance with ISO 527 (ISO, 2012) were determined at room temperature using a universal testing equipment (Sun 2500, Galdabini, Cardano al Campo, Italy) equipped with a 1 kN load cell and a video extensometer (Mintron OS-65D, Mintron, Taipei, Taiwan) to measure the strain. Table 6 summarizes these mechanical tests.

All mechanical tests started with a preload of 1 N. The maximum tensile loads were determined at a test speed of 50 mm/min (tests Ma01-Ma09 and Ma10-Ma12, Table 6). The tensile properties of aged PET and Tb were determined on a minimum of five die cut type 1BA specimens at a test speed of 10 mm/min while HDPE was tested using the same specimen type at 100 mm/min test speed, whereas the tensile modulus (E) was determined at 1 mm/min. Three types of shear tests (M13-M15) were performed on two overlapping Tb sheets joined with a single staple. In one case the staple was placed parallel to the tensile load (referred to as X direction) and in the other two cases the staple was oriented normal to the tensile load (referred to as Y and Z directions). Figure A.1 in Appendix B shows details of these three specific test setups.

It is well known that the mechanical properties of a semi-crystalline thermoplastic are governed by various aspects such as the degree of crystallinity. Therefore, differential scanning calorimetry (DSC) was employed on new and aged PET in order to determine the degree of crystallinity. DSC was performed on a Q2000 TA Instruments device calibrated with indium according to the following cycle: heating from 30 °C to 290 °C at 10 °C/min, 3 min isothermal step at 290 °C, cooling to 30 °C at −10 °C/min, 3 min isothermal step at 30 °C, final heating from 30 °C to 290 °C at 10 °C/min. The sample weight placed in the DSC aluminium crucibles was around 8 mg. The cold crystallization and melting temperatures (T_{cc}, T_m) and corresponding enthalpies (ΔH_{cc}, ΔH_m) were determined from the first heating run. The degree of crystallinity (X_c) of PET was evaluated from the first heating run according to Equation (1).

$$\chi_c = \frac{\Delta H_m - \Delta H_{cc}}{\Delta H_{m0}(1-x)} * 100 \; \chi_c = \frac{\Delta H_m - \Delta H_{cc}}{\Delta H_{m0}(1-x)} * 100 \quad (1)$$

In this Equation (1), ΔH_m (in J/g) is the measured melting enthalpy, ΔH_{cc} (in J/g) is the measured cold crystallization enthalpy, and ΔH_m^0 is the melting enthalpy for a fully perfect crystalline PET which is found in literature to be 140 J/g [63].

3. Results and discussion

This section presents the results of the tests shown in Tables 5 and 6 for the specimens presented in Section 2.1. This section also discusses these results in order to determine whether the studied containers, joints, elements and devices will be applicable to the case study façades and workshops.

3.1. Aging tests

The results of the 500 h long aging laboratory tests are shown in Table 7. Table B.1 in Appendix B presents images of the original and

Table 5
Tests and standards followed or used as guide and specimens studied in aging tests.

Test type	Specific information	Time	Specimens			Test code
			Units	Components	Size (mm)	
Methods of exposure to laboratory light sources applied to plastics	Standards used: ISO 4892-1:2016 & ISO 4892-2:2013	500 h	3	C01	60x20x0.07	A01
			3	J1p	Ø2.3x300	A02
			6	J2p	Ø31.5x12	A03
			3	J3s	73x73x53	A04
			3	J4s	60x20x0.02	A05
			6	J5s	60x20x0.02	A06
			6	J6s	120x14x2	A07
			6	J7s	120x14x2	A08
			6	J8s	120x14x2	A09
			3	E01	70x13x0.8	A10
			3	E02	70x13x0.8	A11
			3	E03	70x13x0.8	A12
			3	E04	70x13x0.8	A13
			3	E05	70x13x0.4	A14
			3	E06	70x13x0.4	A15
			3	E07	70x13x0.4	A16
			3	E08	70x13x0.4	A17
			3	E13	60x60x10	A18
			6	Tp	Ø2.3x300	A19
Exterior exposition to natural weathering	Located in an exterior representative site	500 h	10	Tp	Ø3.2x203	A20
			10	J9s-X	180 x 90 x 1	A21
			10	J9s-Y	180 x 90 x 1	A22
			10	J9s-Z	263x32x0.8	A23
		12 months	1	C01	347x245	A24
			1	C02	245x235	A25
			1	C03	145x145	A26
			1	C04	195x90x60	A27
			1	C05	Ø80x245	A28
			3	C06	Ø53x177	A29
			1	C07	73x73x53	A30
			1	J10s	380x10x3	A31
			1	J11s	380x10x3	A32
			1	J12s	380x10x3	A33
			1	J13s	380x10x3	A34
			2	E09	70x13x0.4	A35
			2	E10	70x13x0.4	A36
			2	E11	70x13x0.4	A37
			2	E12	70x13x0.4	A38
	Located in the final site and position		3	D01	1900x220x150	A39
			8	D02	200x107x100	A40
Interior exposition			4	D03	240x200x3	A41

Legend: X: direction X; Y: direction Y; Z: direction Z; see Fig. B42 in Appendix B.

Table 6
Mechanical tests of aged specimens.

Property	Standard	Specimens				Test code
		Units	Components	Size (mm)	Previous aging test	
Tensile	None	10	Tp aged	Ø3.2x203	A20	Ma01
		10	J1p aged	Ø2.3x300	A02	Ma02
		6	J2p aged	Ø31.5x12	A03	Ma03
		3	J3s aged	73x73x53	A04	Ma04
		3	J4s aged	60x20x0.02	A05	Ma05
		6	J5s aged	60x20x0.02	A06	Ma06
		6	J6s aged	120x14x2	A07	Ma07
		6	J7s aged	120x14x2	A08	Ma08
		6	J8s aged	120x14x2	A09	Ma09
	ISO 527	10	C04 aged	Sample type 1BA, ISO 527-2	A27	Ma10
		10	C05 aged		A28	Ma11
		10	C06 aged		A29	Ma12
Shear	None	10	J9s-X aged	180 x 90 x 1	A21	Ma13
		10	J9s-Y aged	180 x 90 x 1	A22	Ma14
		10	J9s-Z aged	263x32x0.8	A23	Ma15

Legend: X: direction X; Y: direction Y; Z: direction Z; see Figure A.1 in Appendix B.

Table 7
Main results of the 500 h laboratory aging tests.

Test code	Cp.	Set	Base material				Joints			Finishing				
		ShSp	Sf	Sw	Dist	Yell	Drk	Bl	Cor	Del	CrP	Pl	Brs	Yell
A01	C01	–	500h	–	500h	–	N/A	N/A	N/A	–	–	500h	AC	–
A02	Tp	–	500h	–	–	500h	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A03	J1p	–	500h	–	–	500h	–	–	–	N/A	N/A	N/A	N/A	N/A
A04	J2p	–	–	–	–	–	–	–	–	N/A	N/A	N/A	N/A	N/A
A05	J3s	–	–	–	–	500h	–	–	–	N/A	N/A	N/A	N/A	N/A
A06	J4s	–	–	–	–	500h	–	–	RC	N/A	N/A	N/A	N/A	N/A
A07	J5s	–	–	–	–	500h	500h	–	RC	N/A	N/A	N/A	N/A	N/A
A08	J6s	250h	–	500h	500h	–	500h	500h	RC	500h	–	–	–	–
A09	J7s	250h	–	500h	500h	–	500h	500h	RC	500h	–	–	–	–
A10	J8s	250h	–	500h	500h	–	500h	500h	RC	500h	–	–	–	–
A11	E01	500h	–	500h	–	–	–	–	RC	–	500h	250h	Drk	–
A12	E02	250h	–	250h	–	–	–	–	RC	–	–	250h	Drk	500h
A13	E03	500h	–	500h	–	–	N/A	N/A	N/A	–	500h	250h	Drk	–
A14	E04	250h	–	250h	–	–	N/A	N/A	N/A	–	–	250h	Drk	500h
A15	E05	250h	–	–	–	–	N/A	N/A	N/A	–	–	500h	Brg	500h
A16	E06	250h	500h	–	250h	–	N/A	N/A	N/A	–	–	–	Brg	500h
A17	E07	250h	–	–	–	–	N/A	N/A	N/A	–	250h	–	Brg	500h
A18	E08	250h	500h	–	250h	–	N/A	N/A	N/A	–	250h	–	Brg	500h
A19	E13	–	–	500h	500h	–	500h	500h	RW	N/A	N/A	N/A	N/A	N/A

Legend: Cp.: components; ShSp: sheets separated; Sf: stiffness; Sw: swollen; Dist: distortion; Yell: yellowed; Drk: darkened; Bl: bluish; Cor: corrosion; Rc: red corrosion; RW: red and white corrosion; Del: delamination; CrP: cracked paint; Pl: painting losses; Brs: Brightness; AC: All colors lost; Brg: Brightened; Drk: darkened; 250h: degradation appeared after 250 h, 500h: degradation appeared after 500 h, "-": no degradation, N/A: not applicable.

Table 8
Main results of the natural weathering aging tests.

Test code	Components	Test time		Base material				Joints		Finishing		Green growth
		Design	Aborted	ShSp	Sw	Dist	Yell	RC	Unf	Pl	Brg	
A20	Tp	500 h	–	–	–	–	500h	N/A	N/A	N/A	N/A	N/A
A21	J9s-X		–	–	–	–	–	6 mo	–	–	–	N/A
A22	J9s-Y		–	–	–	–	–	6 mo	–	–	–	N/A
A23	J9s-Z		–	–	–	–	–	6 mo	–	–	–	N/A
A24	C01	12 mo	8 mo, SB	–	–	–	5 mo	N/A	N/A	12 mo	5 mo	N/A
A25	C02		5 mo, SB	6 d	6 d	6 d	1 mo	N/A	N/A	3 mo	1 mo	N/A
A26	C03			–	6 d	6 d	1 mo	N/A	N/A	1 mo	1 mo	N/A
A27	C04		–	6 mo	9 mo	5 mo	–	N/A	N/A	–	8 mo	N/A
A28	C05		–	–	–	–	9 mo	N/A	N/A	N/A	N/A	N/A
A29	C06		–	–	–	–	8 mo	N/A	N/A	N/A	N/A	N/A
A30	C07		–	–	–	–	8 mo	N/A	N/A	N/A	N/A	N/A
A31	J10s		–	–	9 mo	–	–	6 mo	–	N/A	N/A	N/A
A32	J11s		10 mo	6 mo	9 mo	5 mo	–	–	6 d	N/A	N/A	N/A
A33	J12s		10 mo	6 mo	9 mo	6 mo	–	–	3.5 mo	N/A	N/A	N/A
A34	J13s		10 mo	6 mo	9 mo	1 mo	–	–	6 d	N/A	N/A	N/A
A35	E09		–	6mo	–	–	–	N/A	N/A	–	–	N/A
A36	E10		–	6mo	–	–	–	N/A	N/A	–	–	N/A
A37	E11		–	6mo	–	–	–	N/A	N/A	–	–	N/A
A38	E12		–	6mo	–	–	–	N/A	N/A	–	–	N/A
A39	D01		–	6 mo	9 mo	5 mo	–	6 mo	–	10 d/-	10 mo	N/A
A40	D02		–	–	–	–	8 mo	7 mo	3 mo	N/A	N/A	5 mo
A41	D03		–	–	–	–	–	–	–	–	–	–

Legend: h: hours; d: days; mo: months; ShSp: sheets separated; Sw: swelling; Dist: distortion; Yell: yellowing; Rc: red corrosion; Unf: unfixed; Pl: painting losses; Brg: Brightened; AC: All colors lost; Pld: plants dying; SB: sample broken; 6d: this degradation happened from the sixth day; 6mo: this degradation happened after six months; "-": no degradation; N/A: not applicable.

aged samples. As shown in Table 7, these tests caused degradation to the sample sets, base material, joints and finishing. The resulting degradation from the laboratory aging tests consisted in: a) the separation of sheets in 11 types of sample sets; b) increase of stiffness, swelling, distortion and/or yellowing of the base material in 15 sample types; c) darkened, bluish and/or corrosion of joints in nine types and d) delamination, cracked surfaces, painting losses, brightness changes and/or yellowed surfaces of the finishing in nine sample types.

Table 8 and Table B.1 in Appendix B present the results of the natural weathering aging tests as well as images of the original and aged samples. Table 8 shows that these tests degraded the studied sample sets, base material, joints, finishing and green growth. The following types of

Table 9
Maximum loads from mechanical tests Ma01-Ma09 and Ma13-Ma15 of aged samples compared to new samples.

Specimens		Test code	Average load	Aged to New
Code	State		(N)	(%)
Tp	New	M09	858 ± 49	
	Aged	Ma01	769 ± 52	−10%
J1p	New	M10	753 ± 64	
	Aged	Ma02	623 ± 26	−17%
J2p	New	M01	629 ± 32	
	Aged	Ma03	613 ± 31	−2%
J3s	New	M04	141 ± 10	
	Aged	Ma04	17 ± 5	−88%
J4s	New	M08	123 ± 14	
	Aged	Ma05	152 ± 22	+24%
J5s	New	M03	67 ± 19	
	Aged	Ma06	80 ± 13	+20%
J6s	New	M05	352 ± 32	
	Aged	Ma07	309 ± 22	−12%
J7s	New	M06	389 ± 42	
	Aged	Ma08	270 ± 8	−30%
J8s	New	M07	362 ± 26	
	Aged	Ma09	324 ± 21	−10%
J9s-X	New	M16	25 ± 2	
	Aged	Ma13	27 ± 1	+8%
J9s-Y	New	M17	32 ± 1	
	Aged	Ma14	29 ± 2	−9%
J9s-Z	New	M18	17 ± 2	
	Aged	Ma15	19 ± 1	+12%

Comment: The maximum tensile loads of new samples were tested on a previous research step [21].

degradation were involved: a) sheet separation in 11 types of sample sets; b) stiffness increase, swelling, distortion and yellowing of the base material in 14 sample types; c) red corroded or unfixed joints in 6 types; d) painting losses and/or brightened finishing surfaces in 5 sample types and e) green growth dying in the green curtain case.

If we compare the aging tests carried out in the laboratory to those under natural weathering conditions, most samples had similar behavior such as the materials PS, HDPE, PET, Tb and stapled joints - J6s and J10s -; with the exception of wood glue - J7s and J11s -, which had visible surface degradation in the 250h and 500h laboratory test controls but lost their fixing capacities in six days during the natural weathering test. The most feasible explanation for this exception is that the eyelets located in J7s probably improved the performance of the wood glue.

These aging tests have multiple results although there are some groups of materials and joints according to their degradation behavior. There were few materials and joints that showed very low visible degradation during the tests: J2p apparently had none during the 500h laboratory test while both HDPE, PET bottles and PS yellowed after eight months of exterior weathering. On the other hand, materials such as cardboard and paperboard had swelled, separated, delaminated and distorted parts after six days of aging had passed. In the case of Tb, the degradation when exposing the aluminum side (A39 test on D01) was much lower compared to the aging problems when exposing the paper side (A27 test on C04). The studied children-friendly paints had different degradation patterns. Paints based on acrylic (Apv) and poster (Ppv) solutions mainly darkened while TiO_2-based paints did not show any darkening during aging (E05 to E12). Moreover, TiO_2 colored paints even brightened after aging tests (E05 to E08). Conventional paints for children such as acrylic and poster paints had significant degradation such as yellowing, paint losses and cracks within aging periods shorter than one year. The exception was the Apv when applied to D03 in the painted face of the louvre which was less exposed to exterior weathering. The best performance was found for Ti1b, a TiO_2-based paint containing Disperlith foodgrade Elastic on the aluminum surface sanded and treated with Disperlith Primer before painting.

The Tb louvres D01 exhibited minor, superficial but not structural degradation during the 12 months project period. The green curtain D02 had an outstanding durability and an unexpected low green growth. The PET bottle-based plant pots had outstanding structural performances in 12 months period without swelling or distortion problems. However, the local high resistant plants did not properly resist the non-watering design that aimed to avoid both the maintenance of manual watering and the complexity of artificial watering [64]. As expected, the interior curtains D03 showed no degradation.

3.2. Mechanical tests

The results of the mechanical tests on aged samples, namely maximum tensile load in tests Ma01-Ma09 and maximum shear load in tests Ma13-Ma15 as presented in Table 9 were compared to results from new samples in previous tests M01-M10 and M16-M18 [21]. As shown, the test Ma01 which was aged polyamide threat (referred to as Tp) showed the best mechanical performance in all tested samples considering the average load of 769 N. Test Ma02 consisted of two aged pieces of Tp knotted together and resulted in a relatively lower average load of 623 N. This illustrates the weak mechanical performance of knotted threads as compared to aged single threads. A similar result had been found for new single threads as compared to new knotted threads in our previous research article [21]. Regarding the main aged joint (J2p) which consisted of Tp knotted to two bottle caps inserted in an aluminum profile, its strength dropped to 613 N. The strength of other joints decreased even further in the following order: five aged Tb strips stacked together with universal glue (J8s), five aged Tb strips joined together with staples (J6s), five aged Tb strips glued together with wood glue (J7s), a rectangular aged HDPE sheet (J4s), aged PET (J5s) and

Table 11
Tensile properties of new and aged Tb, HDPE and PET.

Test code	Material	Components	Tensile modulus E (GPa)	Tensile strength σ_M (MPa)	Failure strain ε_B (%)
Ma10	Tb	C04	2,1 ± 0,3	32 ± 2	4 ± 1
		C04 aged	0,5 ± 0,2	18 ± 1	5 ± 1
Ma11	HDPE	C05	0,9 ± 0,3	36 ± 4	815 ± 99
		C05 aged	1,1 ± 0,2	29 ± 2	401 ± 310
Ma12	PET	C06	1,6 ± 0,6	148 ± 10	28 ± 3
		C06 aged	1,9 ± 0,5	135 ± 5	33 ± 4

Comment: The tensile properties of new samples were tested on a previous research step [21].

Table 10
Thermal properties of new and aged PET.

	1st heating						Cooling		2nd heating		Crystallinity
Sample	T_g	T_{cc}	ΔH_{cc}	T_m	ΔH_m	ΔH_m - ΔH_{cc}	T_c	ΔH_c	T_m	ΔH_m	X_c
	[°C]	[°C]	[J/g]	[°C]	[J/g]	[J/g]	[°C]	[J/g]	[°C]	[J/g]	[%]
new PET	76,2	107,0	4,0	246,8	45,8	41,7	174,4	39,7	246,5	38,0	29,8
aged PET	78,4	101,2	1,3	245,5	50,9	49,6	177,0	46,1	246,2	42,1	35,4

aged PS yogurt cup with a small hole in the bottom and Tp knotted to a bottle cap (J3s).

As expected, the resulting average load of the aged samples was relatively lower in most cases. In the primary joints of these waste-based devices (i.e. Tp, J1p and J2p) this reduction was small, ranging from −2% to −17%. This confirms the reliability of these main joints after their degradation under weathering conditions. In most secondary joints this reduction is acceptable because the average load after aging is minimum a 70% of the initial load, which are loads still acceptable for these joint requirements [21]. The sole exception was joint J3s which lost 88% of its load capacity after the aging experiments and was therefore excluded from being used for these devices in exterior locations. On the other hand, the average load capacity of the J4s and J5s joints slightly increased after aging despite the relatively large experimental error. Regarding J5s, this aging-induced strength increase may be explained by an increased crystallinity of the PET. Bottle-grade PET is usually not modified with additives such as ultraviolet (UV) stabilizers which are needed for outdoor applications. However, unstabilized PET is prone to photodegradation which can cause a molecular weight reduction. The latter is known to cause brittleness, surface cracks, surface deterioration, loss of transparency, yellowing or color change. If the photodegradation takes place above the glass transition temperature (i.e. $T_g \approx 65–70\ ^{\circ}C$) the so-called chemi-crystallization occurs and the degree of crystallinity increases. This increased crystallinity can account for a higher stiffness and strength at the cost of a decreased failure strain [65]. Therefore, the thermal properties of new and aged PET samples were determined using DSC tests; the results are presented in Table 10. It was found that the degree of crystallinity increased from 30% to 35% due to the aging.

The samples Ma10-Ma12 were studied using tensile tests to determine the tensile modulus (E), tensile strength (σ_M) and failure strain (ε_B) of the aged samples, whereas the new samples had previously been tested in Ref. [21]. The results of these tests on both new and aged Tb, HDPE and PET are compiled in Table 11.

These results show that the aged samples have a relatively lower tensile strength as compared to their unaged counterparts due to degradation processes of the materials which were caused by the UV ageing. The tensile strength of C04 (Tb), C05 (HDPE) and C06 (PET) was reduced by 46%, 19% and 9%, respectively.

Similarly, the stiffness of aged C04 was significantly reduced by 76% whereas it increased by 18–19% in the case of HDPE and PET, respectively. As already mentioned, the relatively higher stiffness of aged PET can be explained by a crystallinity increase due to photodegradation-induced chemi-crystallization. Although a similar stiffness increase was observed for HDPE, the underlying causes are different. In the case of HDPE the UV radiation ruptures bonds between carbon atoms of the backbone chain and side groups which produces double bonds between adjacent carbon atoms at the backbone chains, and even crosslinks or hydrogen bonds between adjacent chains. All these events lead to an increased stiffness of the polymer [66,67]. Finally, the failure strain of C05 drastically decreased by 51% due to the aging.

These results coincide with former research projects [33] in which HDPE significantly degraded during one year of exterior weathering. During this time its carbonyl index increased, its molar mass decreased significantly and its strain at rupture decreased linearly to almost zero in only 50 days. As explained in the introduction, there is technical previous literature on plastics materials degradation and, in the specific case of the studied waste materials, the authors have found for PE bags [32], HDPE [33], PET [34] and PS [35]. However, this technical literature focuses on the chemical processes behind this degradation while,

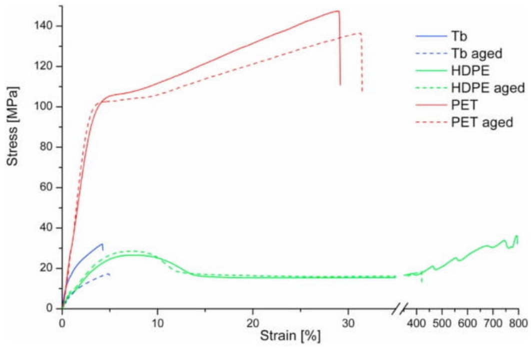


Fig. 1. Representative tensile stress-strain curves of Tb, HDPE and PET new and 12 months aged specimens.

as previously said, this research paper focuses on the applicability point of view for this waste as façade elements for workshops. Similarly, to the authors' best knowledge, most of the new results presented in this research paper cannot be compared to previous studies because those previous studies that have analyzed the mechanical properties reduction of plastics [27,36,37] have analyzed other polymers.

Fig. 1 presents the tensile stress-strain curves of new and 12 months aged C04 (Tb), C05 (HDPE) and C06 (PET) according to ISO 527. As shown in Fig. 1, C05 exhibited a large plastic deformation up to around 400% strain with subsequent strain hardening, whereas aged C05 did not exhibit strain hardening. In the case of C04 (Tb) and C06 (PET) the failure strain was not significantly affected by the aging. Table B.1 in Appendix B present images of the original and tested samples.

According to these experimental campaign results, most aging and mechanical tests gave similar results in the case of similar specimens aged both through laboratory and natural weathering. This campaign has permitted the researchers to classify the containers, joints, elements and devices in two main groups, exterior weather-resistant and not weather-resistant. In the first group, exterior weather-resistant components with minimum stiffness loss, yellowing or distortion and maximum tensile properties are: a) Tp; b) C05 and J4s made of HDPE; c) C06 and J5s of PET; d) the main joint J2p; e) J9s and J10s of staple Tb; and f) E07 and E09-E12 of Tb finished with TiO_2. All studied weather-resistant waste materials fulfill the project durability norms although they have different degradation behavior. HDPE and PET were considered to be the least degradable in accordance with previous studies, to Tbs being somewhat more degradable due to their cellulose-based components although no previous studies have been found in the literature. The only applicable finishing with the minimum paint losses and brightness is TiO_2 in Ti1b, Ti2a and Ti2b types. In the second group, the not weather-resistant components are the PS and the Apv, Ppv and Ti1a finishings. Although PS showed a similar visual observation aging as PET and HDPE, it had significant losses in mechanical properties. Not weather-resistant joints were those involving J3s of PS and glues (J7s, J8s and J11s-J13s). This was because, in exterior weathering conditions, these materials and joints degraded and became useless before one year went by, which is the required time for these specific workshops. In a different way, this study specific alternative of PET bottle-based plant pots appears not to be an acceptable design because the greenery has not grown properly as previously explained in section "3.1". These findings are exclusively applicable to the case study explained in the introduction, which are façade elements for the described educational workshops [11].

4. Conclusions

The aim of this project was to study the aging behavior and mechanical performance of household waste-based façade components developed in elementary school workshops with an expected durability of one year. The focus was on the degradation and mechanical properties of aged samples in natural exterior weathering and equivalent laboratory tests. The mechanical properties of aged Tetra Pak are reported for the first time to the best of the authors' knowledge. As expected, the tensile strength of the used materials composed of HPDE, PET and Tetra Pak decreased due to the UV aging. Nevertheless, these materials are approved to be used for the case study in exterior conditions as well as the main joints and stapled joints. Tbs can be used if their aluminum faces are exposed or painted with TiO_2. This study discards PS and the rest of joints and finishes for exterior use due to their degradation and final mechanical performance. Furthermore, most household waste candidates studied have more than fulfilled the required durability, which could make them feasible façade alternatives for cases beyond this project after the proper studies in future works. In this sense, next research steps will investigate longer life spans, other applications such as cladding and roofs, the use of materials from a second production processing cycle, and a proper end of life phase within the circular economy model for these innovative waste-based building skins.

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CRediT authorship contribution statement

Saeid Habibi: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Oriol Pons:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing. **Tobias Abt:** Conceptualization, Investigation, Software, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101573.

Appendix

Appendix A

Table A.1
with the abbreviations used in the text

Abbreviations	Relevant values
PVC	Polyvinyl chloride
PE	Polyethylene
HDPE	High-density polyethylene
PET	Polyethylene terephthalate
PS	Polystyrene
PA	Polyamide
TiO_2	Titanium dioxide
Tb	Tetra brik sheet
Tp	Polyamide threat
HMA	Transparent hot melt adhesive
PP	Polypropylene
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
NL	Neutral location
Apv	Acrylic paint + varnishing
Ppv	Poster paint + varnishing
DSC	Differential scanning calorimetry
UV	Ultraviolet

Appendix B

Table B.1
Specimens before and after aging tests.

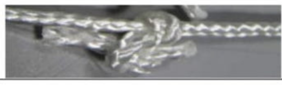
Test code	Specimens before test	Specimens after test
Figure B1. Test A01		
Figure B2. Test A02		
Figure B3. Test A03		
Figure B4. Test A04		
Figure B5. Test A04		
Figure B6. Test A06		
Figure B7. Test A07		

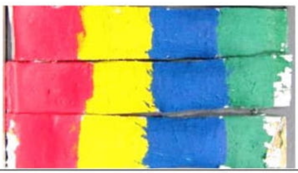
Figure B8. Test A08		
Figure B9. Test A09		
Figure B10. Test A10		
Figure B11. Test A11		
Figure B12. Test A12		
Figure B13. Test A13		
Figure B14. Test A14		
Figure B15. Test A15		
Figure B16. Test A16		
Figure B17. Test A17		

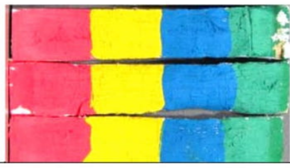
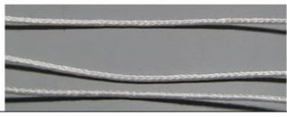
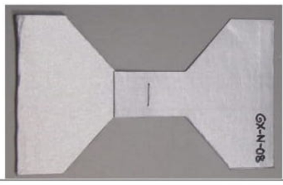
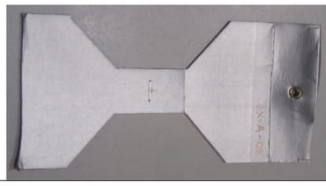
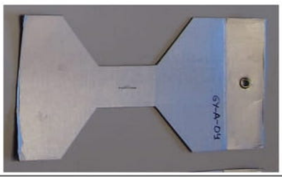
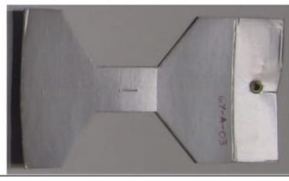
Figure B18. Test A18		
Figure B19. Test A19		
Figure B20. Test A20		
Figure B21. Test A21		
Figure B22. Test A22		
Figure B23. Test A23		

Figure B24.		
Test A24		
Figure B25. Test A25		
Figure B26. Test A26		
Figure B27. Test A27		
Figure B28. Test A28		

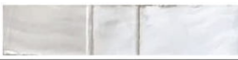
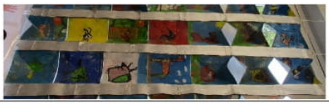
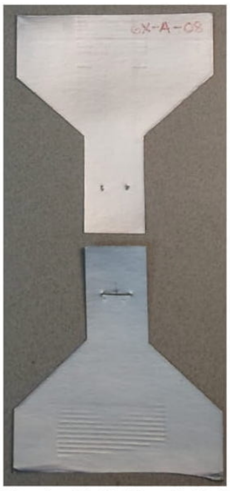
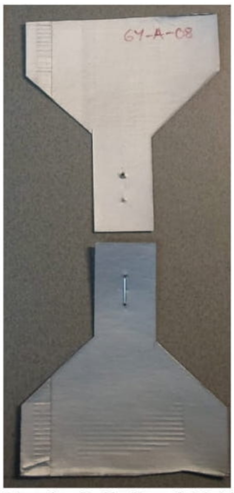
Figure B29. Test A29		
Figure B30. Test A30		
Figure B31. Test A31		
Figure B32. Test A32		
Figure B33. Test A33		
Figure B34. Test A34		
Figure B35. Test A35		
Figure B36. Test A36		
Figure B37. Test A37		
Figure B38. Test A38		

Figure B39. Test A39		
Figure B40. Test A40		
Figure B41. Test A41		



Direction X, *J9s-X aged, Ma13*



Direction Y, *J9s-Y aged, Ma14*

Direction Z, *J9s-Z aged Ma15*

Appendix C

Table C.1
Main parameters of the natural weathering for the aging tests from Meteorological Service of Catalonia [68].

Tests codes	Exposition time		Average daily irradiation	Average daily rainfall	Average temperature			Average humidity	Average wind speed at 10 m	Average wind gust at 10 m
	Starting date	Total			Da	Dx	Dm			
			MJ/m^2	mm	°C	°C	°C	%	m/s	m/s
A20-A23	6/3/2019	500 h	18,37	0,02	12,70	20,79	7,50	57,30	1,77	9,27
A24	11/2018	12	12,29	1,67	12,94	19,18	8,70	69,71	1,56	8,12
A25 & A26	11/2018	mo	11,40	1,39	10,75	16,83	6,49	67,85	1,57	8,24
A27-A34	8/2017		13,33	1,86	16,31	21,96	12,48	68,31	1,58	8,24
A39	5/2018		12,77	1,42	16,16	22,01	12,16	69,31	1,56	8,17
A35-A38 &A40	2/2019		16,78	1,59	16,97	20,33	13,90	68,03	2,89	9,19

Legend: h: hours; mo: months; Da: daily average; Dx: daily maximum; Dm: daily minimum.

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Chapter 6.
Discussion and partial conclusion

This thesis has addressed the economic, environmental and social impacts of the existing conditions in Spanish public primary schools. It was found that optimizing these schools' façades is a key solution to reduce the mentioned impacts of these edifices. This finding is due to the lack of solar control devices that goes from pupils' low comfort to high energy bills. This chapter discusses and outlines some general results that could be implemented to complement and expand the work carried out so far.

Within this context and aforementioned sustainability considerations, the **1st Phase** of this research thesis reviewed ten IF technologies. The focus of studied publications in **Chapter 2** identified that IF economic performances had been investigated from various points of view and values. The time-effectiveness and fabrication costs during the production phase, maintenance and operation cost in the usage phase, and dismantling costs in the end-of-life phase are the most important considerations in the IF development process. However, the distribution of reviewed literature showed that IF technologies are still economically not acceptable and need deeper investigations, in which economic indicators are least analyzed in the IF sustainability publications.

Moreover, the review found that the environmental pillar is a major sustainability dimension, which deals with limited resources, generated waste, and emissions. The reviewed publications showed that environmental impact by IFs was the most considered requirement during the last decade. Most of those studied publications foresee newly integrated IF technologies with more energy efficiency in the near future. Integrated BIPV/ T-DSF systems [105], auto-blind electrochromic setups [106], or PCM-SMAs in wind walls [107] were detected as the top recent trends in IF fields. IFs are also known as emission-reducing methods in construction which highly depends on each IF technology, their design, surface area, building height, and the climate conditions at that particular site, while photocatalytic TiO_2 cover and PBR panels are pioneering technologies in terms of active sequestration of CO_2 and other chemical pollutants. IF technologies are normally delivered with highly supplementary elements such as controllers, inverters, equipment, etc., that require intensive EE (embodied energy) and EC (embodied carbon) impacts. However, novel approaches featured to minimize IF development impacts among them focus on their high recyclability and reusability rate [108].

In terms of social performance, previous studies have outlined that expanding user-friendly IF projects with their innovative technologies are a challenging task with relatively high risks. This research thesis has found the effect of IF application on the user's visual, acoustical, and thermal comfort level as one of the main important considerations before decision making. Literary articles also have evaluated more technical factors such as solar transmittance, shading effect, glare, transparency, fresh air, thermal transmittance, air circulation, humidity level, etc. Social performance studies also have introduced assembling ease, functionality, user safety, and resistance as highly effective indicators to understand the social performance by a technology. However, a long list of studies has identified IFs as sophisticated technologies in terms of design, fabrication, implementation, simulation, reparation, and replacement.

In general, the preliminary analysis showed that the sustainability performance by IF technologies is conditional and differs based on different contexts, perspectives, climates, periods, and regulations. In this subject, the **2nd Phase** expanded the theory(ies) driving the IF field and allowed us to place the research thesis question into context. In this phase, three sample case studies have been defined after carrying out real-time observations in 46 school centers in Spain.

This research thesis, in its **3rd Phase**, generated 101 various solutions for the mentioned problem of school samples through adopting novel design tools. Up to 82 solutions represent the main types of solar control devices composed of household waste, incorporating energy systems, and able to be assembled during participatory workshops in primary schools. While 5 solutions are IF alternatives selected from the reviewed literature in the 1st Phase incorporating dynamic devices, energy systems, and air purifying technologies. The rest of our 14 non-logical solutions beyond this research limit have also been generated to prove the rationality of the previous solutions.

Relying on the qualified comprehensive assessment methodologies and incorporating sessions with multidisciplinary experts, the 12 most sustainable solutions have been selected. These best solution types are all exterior louvers, curtains, and dynamic devices. The assessment process on these solutions assigned different economic, environmental, and social indexes for the specific case study of the public primary schools as listed in **Chapters 3** and **4**. The most environmentally friendly solutions are those incorporating waste, Titanium dioxide (TiO_2), and energy generation systems; which have the lowest impacts in LCA analysis. Regarding social requirements, which are crucial for this thesis case study, the best solutions are those that provide maximum safety and comfort while incorporating PV and fans. However, the economic requirement assessment results allow the thesis author to conclude that before refurbishment starts, some solutions need to be optimized. This thesis identified that the most effective action is shifting their developing and assembling processes. Accordingly, the **4th Chapter** proposed new economically optimized solutions through a new combination of the identified 12 solutions.

Accordingly, the **5th Phase** prototyped three waste-based solutions with the highest possible performances for the defined three sample schools in the **2nd Phase**. These samples have been defined due to: a) their gravest lack of solar control devices, and b) the teaching team prone to collaborating on the project. All 3 prototypes have been supervised by a focus group and considering building orientations, student ages, window height, and climatic conditions. Two prototypes have been developed to solve the solar control issue in three different classrooms in three sample schools. All prototypes are vertical louvers that have proven better performances in terms of thermal, light, and view results. The prototypes all are composed of a) filing waste elements, and b) joints to connect the elements together. The joints are primary and secondary joints as staples, bolts, knots, glues, and eyelets. 2 prototypes are exterior devices composed of Tetra brick milk containers and TiO_2 finishing and PET bottles filled with soil & plants. The other prototype is an interior movable device composed of Tetra brick milk containers that incorporate PV tiles and fans to ventilate. It is worthwhile to mention that all processes to collect waste items, cutting, assembling, and painting the prototypes, have been carried out by the same school's community during various sessions of workshops.

The focus group highlighted the importance of preparing two crucial reports to help inexperienced administrators when deciding on the waste-based IF technology to employ for school buildings. The first report dealt with the contributions of workshops on the knowledge of school communities. The second report presented the technical properties of the newly developed devices. That is why **Phase 6** of this doctoral dissertation monitored the outcomes of workshops on students' knowledge regarding global waste issues through multi-level online surveys. The results showed the positive influence of workshops on pupils' knowledge and comfort. However, future steps about detailed thermal comfort and academic performance analysis will be necessary to determine the extent of these improvements. This phase also dealt with the mechanical and degradation behaviors of the prototyped solutions in order to determine how the joints and elements perform after being applied to the case study façades. The experimental campaign carried out in **Chapter 5** resulted in the degradation of studied sample sets, base material, joints, finishing, and green growth. Both interior Tetra Brick louvers exhibited minor, superficial but not structural degradation during the 12 months project period. In these louvers, the TiO_2-based finishing did not show any darkening or even brightening after aging tests.

The PET bottle-based green alternative had outstanding structural performances in 12 months period without swelling or distortion problems. However, the local high-resistant plants did not properly resist the non-watering design that aimed to avoid both their maintenance via manual watering and the complexity of artificial watering. Regarding the joints, the mechanical tests resulted in the weak mechanical performance of knotted threads as compared to aged single threads. The strength of other joints such as universal glue, staples, and wood glue has decreased even further respectively.

This campaign permitted the researchers to classify the joints and devices into two main groups, exterior weather-resistant and not weather-resistant. In the first group, exterior weather-resistant components with minimum stiffness loss, yellowing or distortion, and maximum tensile properties are Tetra Brick finished with TiO_2, HDPE, and PET. In the second group, the not weather-resistant solutions are the Apv and Ppv finishing and PET bottle-based green curtain which is appeared unacceptable solutions for exterior installations.

The following general considerations also have resulted from monitoring the developed devices:

1. The position of the layer has an important role in the overall thermal performance by solar control devices.
2. In winter, the thermal inertia provided by extensive waste-based solar control devices is not useful in preventing energy losses.
3. Several limitations in relation to the extensive green solar control devices indicate that they are extremely dependent on the climate.
4. The experimental studies demonstrated the high potential of developed devices in increasing the both lighting and thermal comfort level of pupils during the summer and winter seasons.
5. A direct relation between energy savings and the developed façades was observed for all alternatives.

Accordingly, the developed assessment models, workshops, and monitoring phases proposed a high-performance façade alternative for the case study with the following characteristics:

1. Be responsive to indoor and outdoor environment changes.
2. Incorporate renewable energy systems.
3. Control the loss and the gains of thermal energy during heating times with its insulation and airtightness.
4. Provide secure, healthy, and comfortable inner classroom conditions for pupils.
5. Provide an optimal visual comfort adjusted to conditions in a classroom and permit natural light to enter as well as stop undesired solar radiation.
6. Provide optimal olfactory comfort, reduce pollution concentration, and permit natural ventilation
7. Adjustable and modifiable.
8. Provide the possibility of incorporating low-cost materials to reduce production costs.
9. Easy to assemble and to incorporate schools' community.
10. Develop maximum safety considerations that do not pose any danger to pupils.

The monitoring phase also proved that the developed methodology for this thesis in the **1st Chapter** (Fig. 2) is adaptable to the particularities of other contexts after specific adjustments such as:

a. Limitations, scopes, exclusions, and inclusions
b. Specific context problems and the context of economic, environmental, and social regulations.
c. Assigned weights based on objectives, scientific reasons, and panel feedback.
d. Value functions based on the updated boundaries and limitations.

Chapter 7.
Conclusion

In **Chapters 1 to 5** of this dissertation the outcomes of some scientific studies performed during the Ph.D. course, concerning the performance of existing Spanish public primary schools, and the sustainability incorporation of waste-based intelligent façades have been reported including their specific discussions, conclusions and recommendations. The main conclusions of this Ph.D. thesis may be found throughout the chapters, as well as in the conclusion subsection, inside each article. Hence, not to be redundant, this final section summarizes a few overall concluding remarks:

1. Sustainable optimized IFs are appropriate alternatives to retrofit existing Spanish public primary schools and reduce their produced emissions and bills and increase the school community's comfort and subsequent academic progress.
2. MIVES is a comprehensive sustainability assessment model and its novel combination with Delphi, focus group and GMA provides a multidimensional framework capable of producing solution alternatives and reliable data
3. Providing thermal comfort, natural lighting comfort, and fresh air in school buildings are crucial effective factors in students' academic performance.
4. Numerous Spanish school buildings could not satisfy the current indoor environmental regulations for school buildings due to their conformity with obsolete standards and guidelines.
5. IF technologies are practically new technologies and greater efforts are required to analyze and evaluate their diverse possibilities and potentials.
6. Most municipal solid waste materials are potential alternatives to developing building façade components as a novel tool to reduce their final production costs and embodied carbons.
7. Photocatalytic TiO_2 paint is a pioneering and abundant technology in terms of active sequestration of CO_2 and other chemical pollutants.
8. Workshops on human effects on global energy, waste, and emission problems in primary schools have much more preventing effects, and promoting these workshops all around the world will help to have a better sustainable future.
9. Convincing administrators and teaching teams in schools in order to hold workshops and retrofit their façade with waste materials was a challenging process that this thesis dealt with and future investigations will try to overcome this issue by providing much more proven facts and references from the carried-out research.
10. Developed waste-based solar control devices in three primary schools have had positive outcomes on students' lighting and thermal comfort levels which will also affect their academic progress.

A strategy to optimize the sustainability performance of construction consists in providing them with solutions aimed at accomplishing better mitigation and adaptation to the actual climate change, consuming less energy, and also considering the occupant's comfort. Buildings' external components are those more subjected to control the environmental fluctuations, tenants' health, and energy bills, especially in the case of existing buildings.

Within such a scenario, the main objective of this thesis was to obtain an approximation that allows clarifying the questioning about whether the implementation of IF contributes to obtaining sustainable construction, and at the same time, it sought to help achieve a more robust assessment system. Although according to the articles exposed in this document, the application of the IF systems, as specified by various studies, can be considered as mechanisms that effectively contribute to increasing the level of sustainability by the constructions through the mitigation of emissions, reduction of the demands of the necessary resources to the operation. Of course, such solutions also guarantee indoor thermal comfort conditions to occupants.

However, if the vision of the concept of sustainability in construction expands to a larger scale, it is shown that there are still gaps in the IF assessment methodologies. The presented articles showed that the evaluation systems have a significant bias in relation to the weighting assigned to the indicators they seek, obtaining energy efficiency in housing, omitting various qualities that can contribute to the development of sustainable construction with the same impact as obtaining energy efficiency, or even with a higher impact.

The results presented in the articles A of this thesis have supported this statement. In the article "***Sustainability Performance of Ten Representative Intelligent Façade Technologies: a Systematic Review,***" the results indicated that a confirmatory holistic approach would assist in the improvement and advancement of sustainable production in various sectors of the economy, environment, and society. The literature reviewed about IF infrastructures in buildings highlighted the extended research done in the VGS and BIPV systems, whereas scarce literature is available for the application of wind generators in façades. This fact pointed out the novelty of these systems and the necessity to develop new research, since IF implemented in buildings not only provides energy efficiencies but also supplies many benefits to the built environment. Moreover, a disparity in the IF nomenclature was found and an international classification of the different types of IFs to allow technical comparisons between them is highly recommended.

Similarly, the literature review also showed that the use of the sustainability evaluation standard and compliance of design proposals with the standards is profitable. However, among the results obtained, it was found that the indicators used in the evaluations focus on the exclusive sustainability indicators, without considering the global scale.

What is stated in the previous paragraph suggests that the use of the standard be complemented with various evaluation mechanisms that have various objectives to enhance the sustainability of a given building. So, the building can be considered sustainable, in a more holistic and inclusive sense.

Various studies [109−111] point out that without considering global sustainability the buildings cannot meet the basic needs of the inhabitants which will emit more GHG, regardless of whether the building has any environmental labeling or certification.

The second article that constitutes this compendium focused on this program: "***Sustainability Assessment of Household Waste Based Solar Control Devices for Workshops in Primary Schools***". Among the main results obtained, it has been found that the new combination of the GMA, MIVES, and Focus Group is a rigorous and versatile methodology in order to obtain the most sustainable façade refurbishment solutions for a specific problem of existing educational architecture in a specific context.

Employing new types of environment-friendly composites, containing vegetal matter and municipal waste through reusing activities has shown to have good thermal and light control properties, making these new assemblies a quite promising alternative to the mostly used traditional solar control devices. Moreover, the investigated measures carried out in workshops resulted in reproducible, safe, compatible, and efficient practices which can be distributed among various schools all around the world with a lack of solar control devices.

Based on the developed list of indicators and weighing process, the waste-based façade refurbishment of the specific existing public school, which complies with the conventional architectural characteristics in the Mediterranean climate of the Spanish area; requires a final budget increase of nearly 0% to obtain lighting and thermal comforts. However, with a cost increase of nearly 15% applying greenery systems or other smart carbon sequestration systems combining renewable energy systems, CO_2 emissions, and primary energy demand also significantly can be reduced.

In the specific analysis of the relationship between more intelligent systems and their sustainability contributions to existing schools, the third article "***New sustainability assessment model for Intelligent Façade Layers when applied to refurbish school buildings skins.***" revealed that although among the majority of the IFs —which have a sustainable approach— their optimization in terms of final product cost is crucial when implemented in Spanish primary schools. In consequence, this study concluded that optimized IFs could be used to increase the sustainability performance by existing schools. However, none of the assessed systems, nor those analyzed in the articles in **Chapters 2** and **4**, considered the MSW waste materials as an alternative material to reduce their production phase impacts. Analyzing the environmental and economic behavior of each component, researchers confirm that the production phase is crucial in the overall impact, around 80% of the total. Therefore, any replacement of the IF components by MSW waste materials would lead to lower overall environmental and economic impacts. Although it must be noted that the application of MIVES allowed to point out less-motorized, easy-to-assemble, secure, and healthy systems. This application also has identified the automated solar blinds as the most sustainable IF by quantifying the highest sustainability and partial satisfaction indexes as well as the main components, features, and details of these developed technologies. Moreover, the results of the evaluations proved that TiO_2 as an IF technology has a great potential able to reduce emissions and purify air at the same time. The MIVES study demonstrated that the extensive motorized solar blinds reduce by 30% the overall environmental impact in existing schools by 30% compared to a non-insulated conventional façade.

It is also worth noting that the indicators aimed at describing the overall sustainability performance of an IF, have been calculated considering the Barcelona climatic conditions, pupils' requirements in diverse Spanish primary schools, and financial resources.

However, in order to have a more comprehensive understanding of introducing waste as a construction component, other analyses should be carried out aimed at evaluating the mechanical resistance, the impact of moisture content, and the influence of the drying process on the mechanical properties. That is why **Chapter 5** dealt with the aging behavior and mechanical performance of household waste-based façade components developed in **Chapter 2**. This chapter after performing one-year experimental tests for both non-structural and structural components of three waste-based solar control devices showed that there is a high potential to improve the economic and environmental performance of IF services by promoting the employment of waste materials in their production process. This chapter approved the feasibility of all extensive waste-based solar control devices to be used for the case study in exterior conditions as well as their main joints and stapled joints. The waste-based green façade's effectiveness as a tool for improving indoor comfort levels has been also examined.

In general, the approaches and framework utilized in this research thesis represent a crucial step, to be further explored, in the development of procedures for the evaluation of strategies and solutions to be implemented to optimize the sustainability of Spanish primary schools. This document allows for a broader understanding of the inherent relationship between IFs and the existing architecture performance, through rigorous, multidisciplinary, and holistic methodological models, which allows calculating these technologies' sustainability in a more robust concept than is currently considered. On the other hand, this framework permitted the candidate to include the most qualified experts' views and most reliable data with minimum biases, incorporate main indicators from energy efficiency to social values, generate the most appropriate alternatives, and finally propose recommendations to develop optimized IF alternatives with the highest sustainability indexes. The framework allowed proposing and establishing strategies for school administrators to apply circular economy thinking in a simpler way. This thesis showed that MIVES is a tool that can contribute to achieving the sustainable development objectives of the 2030 Agenda and that it is essential to face the challenges through prevention strategies. Moreover, it was confirmed that MIVES is a flexible methodology that allows the use of different resources adapted to the peculiarities of each analysis. Even with this flexibility, it is considered that the results are reliable and replicable not only in a specific geographic region but in the world.

The importance of the published articles also lies in the fact that each one of them presents indicators that can be considered by the existing plethora of sustainability evaluation methodologies, in order to be able to establish common characteristics or areas of interest, since there are enormous differences among the different methodologies.

As for the developed façade components, identifying and utilizing new types of waste materials with behavior comparable to those of the more impactful used traditional ones would allow making nearly zero embodied energy and carbon alternatives. On the other hand, the increase in the use of renewable sources and emission sequestrating materials represents an important instrument for improving the environmental performance of the existing educational construction sector.

Finally, with the understanding that schools and their community present opportunities to enrich both ecology and global change, and are considered critical places to create more sustainable futures. By promoting sustainability through accurate planning and much more innovative workshops in schools with new DIY experiences, according to the peculiarities of the region, researchers can encourage the teaching team community to incorporate these strategies. However, innovative techniques such as virtual approaches to avoid the necessity of teaching community incorporation in performing workshops will contribute to efficient and accelerated positive outcomes.

On the other hand, proposing new low-cost innovative façades, considering the tight budgets of the Spanish educational system, can provide a way to obtaining successful refurbishment solutions. However, this movement requires a global movement toward more sustainable buildings with intelligent façades which can produce more evidence of the potential these technologies have. It is worthwhile to mention that in Spain, especially in Barcelona during recent years, the number of implemented intelligent façade technologies on commercial and office buildings have been increased as evidenced by Barcelona Institute of Science and Technology, Media-tic, APROP in Barcelona's Gothic quarter, etc. However, to the candidate's best knowledge, none of the developed façade technologies in Spain, implemented in public schools' façades nor private schools, which this thesis considered, is as a limitation to introducing the IFs as high-performance technologies to the targeted schools.

Chapter 8. Future work

During the development of this research thesis, and in parallel to the achievement of the general objectives, some existing gaps have been identified among the analyzed IF systems, as well as evaluation methodologies. The identified gaps allow one to expose the bases referring to new lines of research as:

1. Post occupancy analysis of the satisfaction level from the developed prototypes and analyze their effects on pupils' academic performance.
2. Develop and prototype more and different low-cost IF technologies for different schools not only in Spain but in areas having different climatic conditions as well.
3. Expand carried-out workshops in different countries and regions with different materials considering the local educational regulations.
4. Provide documented approvals of previous projects to convince administrators who are willing to rehabilitate the core of their building façades while dealing with tight budgets.
5. Prepare new approaches and strategies to attract teaching team communities to incorporate into the workshops or educational programs about global sustainability challenges with pupil participation.
6. Prepare a procurement estimate to develop the proposed most sustainable IF alternative in **Chapter 4** and search for different European and non-European foundations as Cost Action, government programs, I+D Companies.
7. Improve the developed framework for the sustainable refurbishment of existing buildings in terms of costs, time, construction process, materials and complexity.

As expected, the works of this thesis will continue to be developed. For example, it has been intended to evaluate in future projects the influence of energy efficiency by school buildings in a real-time project after the application of the developed façade alternatives. In addition, another aim is to evaluate the influence on the comfort conditions, such as lighting comfort, or pupils' health and following academic progress to complement the results already obtained from this study. These aspects would require the evaluation of different parameters such as U and G values, layer thickness, and CFD simulations.

Chapter 5 points out that developed solutions are effective and well-established technologies in the field of sustainable practices, while some aspects to be improved in the future have emerged concerning especially: the need the new exhaustive plant species characteristics databases like climate conditions, shadow factor, water requirements, climbing capacity, etc.; the possibility of using new eco-compatible materials; the importance of life span; and a proper end of life phase within the circular economy model. In this regard considering the lessons learned from this research thesis, the candidate has participated in a proposal called Waste-based Intelligent Solar-control-devices for Envelope Refurbishment (WiSeR) which aims to develop new waste-based intelligent facades to refurbish buildings, by focusing on thermal conductivity and solar thermal gain that highly influence interior comfort and related energy efficiency. WiSeR rethinks the role of waste in architecture envelopes by recycling and reusing waste. This proposal has received competitive funds from the 2021 Spanish Call «Proyectos de Transición Ecológica y Transición Digital» of the Ministerio de Ciencia e Innovación (MICINN) funded by the European Union NextGenerationEU Program.

On the other hand, regarding the study of public primary schools, it is necessary to study a greater number of practical cases of public schools to obtain comparable and conclusive results; as well as to incorporate new materials for the carried-out workshops. In the future, this project will also analyze the contributions of the workshops to the pupils' global waste awareness and will define a definitive version of the workshops based on the latest advances in primary education pedagogy.

As for other recommendations for future projects, there is still a need for a new standardized approach for analyzing both data and results and other factors altogether that can become an opportunity for future studies. However, based on the results and developed framework in this research thesis, among analyzing other existing evaluation systems, the candidate developed a new easy, reliable, fast, and completely online sustainability assessment platform available for researchers, students, engineers, architects, and householders to select the best façade solutions from the global economic, environmental and social point of views. As one of the main future projects, the candidate, by collaborating different research centers and industry partners, will try to develop the platform to be able to analyze the sustainability of different solutions for a different part of the construction industry not only in Spain but also all around the world.

Appendices

Appendix A. Conference paper 1.

Towards more sustainable schools incorporating new solar control devices assembled during workshops recycling waste materials

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Abstract

This research paper presents part of a research project that develops the participative design of innovative solar control devices integrated in school architecture using low-cost tensed structures, composed of reused household waste and renewable energy systems. In consequence, these devices are designed to be built during workshops about waste management and sustainability by elementary and high school students and teachers. In general, this project aims to reduce the negative environmental impacts by educational architecture and, at the same time, increase students and teachers´ comfort levels and sustainability awareness. The specific case studies in this project occur in Spanish schools, which have a particular endemic problem in terms of user comfort due to lack of solar control.

The main novelty of this project is the aforementioned design of solar control devices composed of household waste to be assembled during workshops by students and teachers. Although there have already been previous workshops in which students learn about school buildings, this project moves a step forward and involves students and teachers in the construction process of a solar control device. This article presents three solar control waste based device prototypes, the main steps followed to design and assess them and the first workshop.

Keywords: Sustainability, School buildings, Solar control, Household waste, Participatory workshops, Elementary education

1. Introduction

The generation of waste at a global level is more than 2 billion tons of waste dumped per year. Among the negative consequences this waste pollutes the environment, increases toxicity and worsens health[1]. For example, in 2013 Europe dumped 2.5 billion tons of waste, part of which was recycled and reused, but 1.6 billion tons of waste was dumped into the environment[2]. Urbanized areas create the largest share of waste[3] that is defined as municipal solid waste (MSW)[4]. An important part of MSW is composed of “household waste”[5] that originates from homes daily waste.

MSW and household waste are a crucial challenge for governments, which need the best waste management mechanism. In this sense, a waste hierarchy has been defined in the European waste directive[6] with some clarifications proposed by Gharfalkar[7].This hierarchy has the following options: 1) prevention, 2) reuse, 3) recycling, 4) recovery and 5) disposal. This present project develops options 1 and 2 during workshops because of the following reasons. The first option is developed because it promotes decreasing waste generation by increasing users' knowledge and awareness about these issues. The second option is developed because this project reuses waste and, in consequence, this waste is saved from the waste cycle and taken back to a use cycle.

In this sense, this research project reuses household waste during workshops in order to: a) raise the school community's awareness about our society's waste problem and b) build needed elements for those centers. Thermal comfort, air quality, natural lightning and visual comfort, among others, are essential for school buildings[8]. In the case of Spanish schools there has been an endemic solar control lack which created its consequential problems for years. Many school centers do not meet current indoor environmental requirements because they had been designed to satisfy other uses or followed previous obsolete standards, guidelines and criteria[9]. On the other hand, hundreds of schools were built during recent decades in tight timeframes and budgets due to dramatic needs for school classrooms[8]. Therefore, an important part of Spanish educational interior and exterior spaces do not achieve minimum lightning and thermal comfort at the current time. In most schools, this discomfort could be solved by installing natural light control devices that are able to control these sun radiation effects on opening surfaces: a) the light amount that penetrates into educational spaces, and b) the greenhouse effect thermal gains. These solar control devices could also incorporate renewable energy technologies that could also be part of the aforementioned learning workshops[10].

In this context, this research paper presents the first new prototypes of waste based solar control devices to solve the aforementioned problems. It also presents their design process that has taken into account: a) previous similar projects and construction elements, b) the elementary students and teachers who will do these workshops and c) the first school where it will be applied. Then this article presents an assessment for these first prototypes. Finally, the first version of this workshop is described along with its preparation, implementation and planned future works.

2. Research steps

This research project follows the four steps listed in Figure 1. The first phase reviews technical literature and previous architectural projects to find similar experiences this project could learn from. The second step defines what the boundaries and limits of this project are in order to obtain this case study. Third the first prototypes were designed, built and assessed. From this assessment, the fourth phase designs a second prototype that will be built during the fifth phase as part of the first participatory workshop to build waste based solar control devices for use in elementary schools.

Figure 1: Steps followed to carry out during this research project

3. Previous related projects

Since ancient times, building projects and architecture have reused waste as construction material. Buildings using household waste probably started as part of the rubble fill in rubble masonry, comprised by items such as ceramic dishes, containers… Its use in façades has more modern similar examples such as Antoni Gaudi's "trencadís" from broken ceramic tiles –partly from dishes- and glass bottles. Trencadís was used at the end of the 19th and at the beginning of the 20th century as façade and roof cladding in several architectural projects such as the Sagrada Familia[11]. In those early 20th century years, during the USA gold rush, desert villages constructed numerous shelters using glass bottles[12], followed by numerous similar examples in USA and all over the world until the present[13]. At the beginning of the 2000s there are the first examples of buildings constructed with walls composed of plastic bottles and concrete[14]. More recently, some research has been carried out on plastic bottles innovative structures such as composed beams, exhibition pavilions…[15]. There are also numerous lamps and decorations made of household waste, which the Do-it-Yourself (DIY) social movement provides evidence of[16]. There are also non-lucrative organization initiatives, such as Liter of light, based on construction with household waste[17].

Around the world, there have also been numerous educational workshops that deal in part or specifically about recycling and reducing waste[18], etc. Both these workshops and the aforementioned building experiences can increase participants' awareness about our serious global waste problem and, at the same time, give a new use to this waste. In this sense, they can accomplish this project previously mentioned objectives. These initiatives can collaborate in developing the crucial point of waste education in schools[19] as well as promote its management[20]. Some of these initiatives have resulted in solving required elements in elementary schools such as playground elements[21]. Additionally, the buildings or elements constructed developed during these workshops can act as a third teacher for students[22].

4. Case study

This project will focus on the construction of new solar control devices for Spanish elementary schools to solve the aforementioned lack of solar control in these educational buildings. In Spain, elementary schools, also called primary centers, include grades 1-6 for children aged 6 to 12 years old. These schools are normally joined with kindergartens, which have children aged 3 to 6 years old. From all the thousands of schools that have this solar control lack this first study has considered the Sant Martí School in Torrelles de Llobregat because its teaching community is willing and available to participate in this project and its solar control problem has priority compared to a broader sample of schools as we see in Table 1. This broader sample includes 185 public schools in Barcelona and its metropolitan area, which are at the same time representative of a broader sample of schools in Barcelona and Spain.

Case study	**Solar control satisfaction**		**Solar control devices**	
	In terms of natural light	**In terms of thermal comfort**	**Years used**	**Current state**
School Sant Martí	50%	50%	More than 25	Need replacement
Average value of this sample	58%	36%	15 years	Need maintenance

Table 1: Main features of the Sant Martí School and the schools in this sample

The Sant Martí School is an elementary school which incorporates a kindergarten. Figure 2 presents a general view of this school. It was built in 1986 and enlarged from 1999 to 2001 by the architect Claudi Aguiló Riu. It has a 3.000 m2 surface area. During 2017-2018 academic years, this school had 374 students and 26 teachers, two classes per course year in both kindergarten and primary levels.

Figure 2: General view of the SW façade, whose ground floor windows are studied in this project

One of the worst solar control lacks this school has occurs in ground windows facing south west (SW). Figure 2 shows the general location of these openings. These windows correspond to ten classrooms: two 5th grades, two 6th grades, Special Education, Computer, English, Science and two support classrooms. Figure 3 presents a plan for these classrooms and Figure 2 a general exterior view of their openings. There are 16 windows in total, one or two openings per classroom, all of them are 2.4 m wide and 1.95 m high. At present, these studied windows only have an interior curtain as a solar control device. This research project will start developing a first prototype for a 0.6 m wide part of one 5th grade classroom B opening, which Figure 3 indicates.

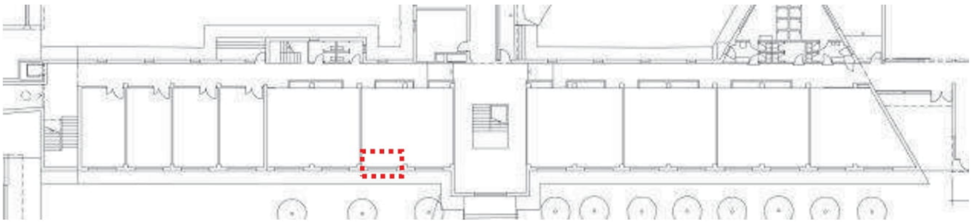


Figure 3: Plan for these ten classrooms facing SW. The red rectangle marks the location for the first prototype developed and installed during this project

5. First prototypes

This project is part of a broader research project in which we study different types of waste based solar control devices such as blinds or awnings, composed of a broader variety of waste materials from plastic bottles to Expanded Polystrene (EPS) plates. The new solar control devices assembled in this project will be exterior to be more effective in avoiding the greenhouse effect[23]. Specifically, these first prototypes will be vertical louvres due to the southwest orientation of the windows in the Sant Martí School and the preferences stated by the Sant Marti teaching team. In this SW orientation neither horizontal nor vertical louvres are the best solution as they both are the best for south and west/east orientations respectively[24]. On the other hand, this school teaching team was not satisfied with the thermal, light and view results of first floor horizontal louvres in this SW façade. Therefore, in this ambiguous orientated case, vertical louvres were chosen for this first prototype, which has been designed in order to improve the performance of the existing solar control devices.

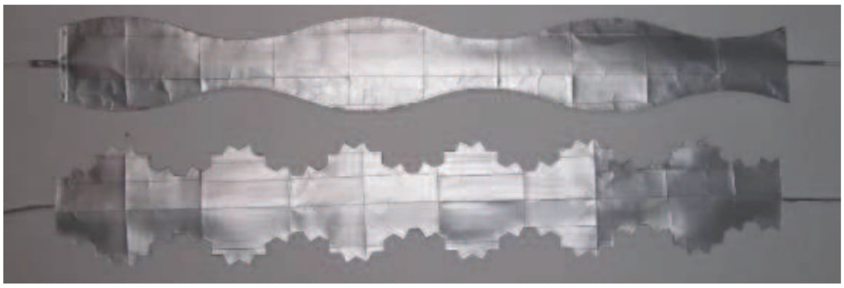


Figure 4: first tetrabrik based louvres prototypes

Children's security has been one of the main parameters taken into account to choose the waste material assembled in these louvres. Therefore, from Spanish household waste, this project will focus on household waste that children can manipulate easily and without any risks such as cuts, allergies… In consequence, this project will use mainly household waste from food containers such as plastic bottles, tetrapaks, plastic boxes, trays, plates, dishes, etc. In this sense, this project will not work with waste that has dangerous shapes or components, for example cans, glass bottles, electronic devices… Solar control devices employed in this project will not incorporate either waste that has contained high allergenic or toxic products, as found in some cleaning and painting solutions. This project will also discard household waste with low durability such as paper and paperboard. Tetrabrik was chosen as the waste material to be used since this school participates in the European Union program "EU School Milk Programme" which makes tetrabriks readily available.[25] This program encourages children to consume dairy products because of their nutritive properties and, among other activities provides the Sant Martí school 40 milk tetrabriks per week. Therefore, the first solar control prototypes assembled in this project are the two types of vertical louvres shown in Figure 4a and 4b.

These prototypes have some common characteristics such as their reusing waste rate. To produce these louvres, 125 tetrabriks per m2 are needed, some 40 tetrabriks per louvre in four crossed layers. On the other hand, they differ in their perimeter shape, which is curved or toothed as can be seen in Figure 5. This perimeter difference involves important particularities when assembling each louvre. These particularities are: production easiness and time, louvre stiffness and operability. Production is much more difficult in the toothed solar device, both regarding the angles to cut and the required cutter tools, which most elementary aged children should not use. Production time is also faster in the curved solar device, since it has a perimeter one fifth the size of the toothed solar device. Stiffness was more difficult to obtain in the toothed model because in order to relate its geometry to the bottom mechanism and the top part, it is wider and it is more difficult to cross its tetrabrik layers. Finally, the toothed model is more difficult to close and mesh all teeth from one louvre to the next, although this is an advantage to block the louvres when user wants them shut. However, the curved model was better in most particularities and, therefore, it was the first prototype to be built in this project workshop and is shown in Figure 5.

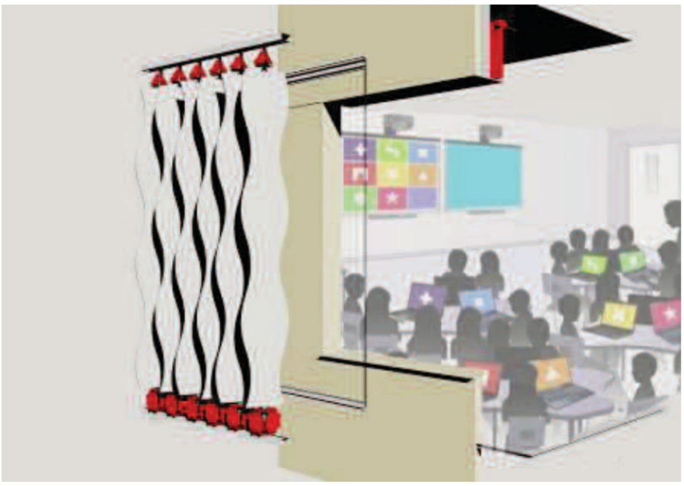


Figure 5: first version prototype chosen to be assembled during this workshop

6. Workshop

This first workshop will serve as a reference for future workshops. It took place on May 25th 2018 from 15:15 to 16:15h in Grade 5B classroom at the Sant Martí School in Torrelles de Llobregat, Barcelona. This workshop involved the following five phases: a) organization, b) preparation, c) construction, d) assembly and e) analysis.

This workshop was organized after having meetings with the Sant Martí School teaching team and the Catalan Education Department. These meetings focused on five topics: elementary education, school buildings construction, sustainable schools, research and resources center and work safety. At these meetings, the project designers defined the structure and content of this workshop. The main contents included in this workshop are aligned with this research project and can be summarized in: raise participating children's awareness about the waste problem our society has, show them an example how to reuse waste and build better solar control devices that will increase their classroom light and thermal comfort. The structure of this workshop had to satisfy the school teaching team's following requirements: be 20 minutes long, be repeated three times for groups of 16 students each on the previously mentioned date and time. In order to accomplish these requirements these workshops consisted only in finishing three main parts for three louvres: their top part, their surfaces and their bottom mechanism[26]. Each group of 16 students finished one set of these main parts and they were divided into three student subgroups: six students finished their solar control device top part, four students finished their louvre surface and six students finished their louvre bottom mechanism. Each student subgroup had a teacher helping them while a fourth teacher provided support to all and took notes and pictures. Figure 6 shows one of each of these three subgroups. Each 20 minutes session was divided into the following parts: 1) exercise explanation; 2) hands on workshop and 3) conclusions.

Figure 6: subgroups of students working on their louvre part while receiving support from their tutors.

There were two parts to the material preparation for this workshop: to explain what to assemble and why plus to describe the materials used. This explanation had a general common part about its aforementioned contents and a specific part divided into subgroups related to each main part these louvres have. This explanation was adapted to students' age and illustrated with waste and solar control device samples. Before starting each workshop session we did a pre-test by asking students two questions: a) if they thought that waste such as tetrabriks could be reused to build new things and b) if they had already used waste to do things such as containers to plant plants in, etc. Table 2 summarizes the results of this pre-test.

Question	Answer	Number of answers							
		Session 1		Session 2		Session 3		Average	
Do you think that waste such as tetrabriks can be reused to build new things?	Yes	2	13%	11	69%	7	44%	7	42%
	No	14	88%	5	31%	9	56%	9	58%
Have you already used waste to do new things?	Yes	4	25%	7	44%	8	50%	6	40%
	No	12	75%	9	56%	8	50%	10	60%

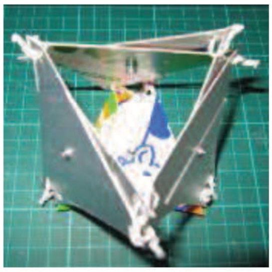
Table 2: Workshop pre-test results

On the other hand, the description of materials used aimed to reduce the number of operations children had to do, so that each student subgroup could finish their louvre part in 20 minutes. Nevertheless, some extra material was prepared just in case children were able to do it quicker than had been expected. This materials preparation involved: M1) waste conditioning, M2) louvres components production, M3) louvres main parts production, M4) workshops sets preparation and M5) samples construction. Waste conditioning (M1) consisted in opening, cleaning and separating mainly tertrabriks, their covers and plastic bags twisters. During components production (M2) top part triangles and bottom mechanism squares were cut and drilled while louvres surfaces layers were also cut. Then, during M3, exclusively louvres layers were put together. M4 organized all these parts in sets ready for workshops and inserted a sheet of instructions. Finally, during M5 the construction of three louvre main parts samples took place so these real size samples could be shown to students during this workshop introduction and practical exercise. Figure 7 shows examples of preparations for these materials.

M1

M2

M4



M5

M3 & M5

Figure 7: Images about materials preparation: M1) waste conditioning, M2) louvres components production, M3) louvres main parts production, M4) workshop sets preparation and M5) samples construction.

The construction phase was the main part of this workshop, during which students finished the main parts for louvres. Figure 8 shows what student subgroups produced during their 20 minute sessions.

Figure 8: Examples of what student subgroups produced while working either on top parts, surfaces or bottom parts of louvres

After finishing this phase, teachers met to assess this workshop in order to implement improvements in future editions. Based on Table 2 data, teachers concluded that most students still did not know that waste can be reused and had not done workshops like this one before. So this workshop proved to be of great importance to overturn this evidence and in the future this questionnaire should be extended to broader samples. Initial explanations and group dynamics were found to be the major weaknesses during this first waste material solar device workshop. In both cases, the aforementioned 20 minutes time limitation reduced real activity time for students during this workshop. This time limitation placed strict time control constraints on these time consuming student activities. The researchers concluded these workshops would become more effective if longer time frames are established. As a final phase in this activity, the assembled louvres were installed in the window as show in Figure 9. However, these louvres are not definitive permanent solar protection devices for this school yet. As prototypes, they must undergo several tests and subsequent improvements.

Figure 10: first prototype assembled

7. Future plans

To improve both solar device prototypes and their workshops will become the next steps in this project. After carrying out mechanical and durability tests and analysing their results, improvements will be incorporated in these solar devices. A seminar of experts shall be convened in order to redesign this workshop taking into account this first experience. For example, this seminar will discuss more active learning methodologies and techniques for the initial explanations so students have a more active attitude and better understand what their roles are. These techniques include showing a movie related to this topic on the importance of recycling waste or to show a model of a solar device louvre on a window. Selecting age appropriate media can explain more adequately the grave waste problems our society faces as well as the need for schools to incorporate solar control devices on their windows to improve their lighting and thermal comfort.

8. Acknowledgments

To Sant Martí School Teaching team and students. To the Department of Education (DE) and their members who are giving useful advices and support to this research project.

9. Funding

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Appendix B. Conference paper 2.

Rehabilitation of educational architecture through waste-based intelligent façade layers

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[(2)]Technical University of Catalonia (UPC), School of Architecture of Vallès (ETSAB), Structural Morphology in Architecture (SMiA), C/ Pere Serra 1-15, 08173 Sant Cugat del Vallès, Barcelona, Spain.

1. Introduction – The economic, environmental and social negative impacts of school buildings have been increasing during the last decades with such dramatic consequences chief of which are the low comfort level of teachers and students besides high energy consumption and GHG emissions. As a proven fact, façade of buildings are responsible for approximately 36% of total energy consumption in buildings which can be reduced considerably starting from optimizing construction materials and components, applying intelligent technologies to improving appearance among others. But experimental projects showing that the optimization of façades requires long-period and high-budget projects. Subsequently, the authors have studied the design of new mountable intelligent devices incorporating low-cost solutions and renewable energy technologies. This work focuses on the possibility of designing a mountable composite intelligent layer for schools façades composed of waste materials. This possibility aims to reduce these buildings both solar-load and energy consumption and at the same time increase thermal, acoustic and visual comfort levels which are the endemic problems of numerous Spanish schools. This paper reviews the related technical literature to study related projects on façade external layers. It also presents the trial designs and prototypes for these external intelligent layers. This paper presents part of Saeid Habibi's PhD studies titled "Towards the most sustainable school architecture using intelligent patterns cladding".

2. Experimental – The experimental programs are:
1. Providing an overview on architectural façade elements that are built reusing waste materials, include renewable energy systems and can be applied on façades external layers.
2. Solve Spanish schools specific and endemic sustainability problems by designing new intelligent low cost external layers and their first prototypes. These innovative layers will be built reusing waste materials such as tetra brick containers, polystyrene containers and PET bottles among others. These prototypes will be based on an experimental campaign that evaluates the mechanic behaviour and durability of their components and materials.

3. Results and Discussion – This research project by taking advantages from the intelligent systems and waste materials, will conceive the façade as a dynamic and interactive architectural energetic system. This function in the format of an external layer can be act as a crucial revitalizer of energy performances, costs and appearance of Spanish school buildings that the research team by doing many field studies, analysis and surveys have proved this necessity. Accomplished analyses are also showing that because of financial problems, low-cost and short-term solutions, methods and technologies are more preferable than high-cost projects.

4. Conclusions – As a conclusion, analyses and built trial prototypes are showing that by positive executing of the presented paper objectives this project will go to optimize students and teachers unacceptable acoustic, thermal and visual comfort levels and their sustainability awareness and more important will contribute in reduction of 3.59 MTOE energy in each year. To sum up, this paper by identifying the sustainability problems of schools (related to façades) and developing low-cost intelligent façade layer proposals, while supports the waste reducing goals, will be great help in convincing administrators who are concerning to solve a sort of problems with minimum cost and time.

Appendix C. Conference paper 3.

Household waste potential for façades refurbishment. The case of Spanish schools solar control devices.

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[(2)]Technical University of Catalonia (UPC), School of Architecture of Vallès (ETSAV), Structural Morphology in Architecture (SMiA), C/ Pere Serra 1-15, 08173 Sant Cugat del Vallès, Barcelona, Spain.

1. Introduction – In developed countries we generate high amounts of waste with which we have serious management difficulties. For example in Europe each person generates 477 kg and in Spain 425 kg in each year. Among this waste there is household waste, which is composed of containers and wrappers that are not toxic to be in contact with food and drinks and could have a second use. One possibility is reusing them as construction material, of which there have been a lot of experiences in this direction until now. The authors of this paper have detected a specific application of household waste reuse as construction material that aims to cover an important social need in Spain. This is the endemic lack of solar control devices that an important number of public Spanish educational centres have. Moreover, the public system has difficulties in providing new solar protections in due time for all these centres, which would be satisfied if these solar control devices had specific and particular designs in each case according to the building, cultural context, educational approach.
In this sense, the authors have started a research project that will design new solar control devices integrated in educational architecture incorporating low-cost tensed structures, composed of reused household waste and renewable energy systems and technologies. Furthermore, these devices are designed to be built during workshops about waste management by primary school pupils and teachers. Therefore, these workshops will also help to aware children, which are the base of our Society and our future, about our high waste generation and how waste can be reused.
This paper presents the first part of this research project, which consist in: 1) a literature review of similar projects and 2) a surveying study to determine the exact affectation of this lack of control devices in public schools. This research project is still in progress and has support from a 2017 Leonardo Grant for Researchers and Cultural Creators, BBVA Foundation.

2. Experimental – The mentioned review on similar projects will focus on three main groups: a) household waste applications in architecture, from structures construction to design elements that could be applied to solar control devices; b) tensed solar control devices, including awnings, blinds, vertical and horizontal louvres among others and c) solar control devices incorporating renewable energy systems, for example photovoltaic, solar thermal and wind, including piezoelectric systems. The previously mentioned surveying studies include questionnaires to schools teaching directive team, different specialities teachers and students. The surveys are being carried out to a representative sample of public schools from big cities, medium size towns and villages with different number of inhabitants, density, births and deaths rate, solar irradiation, maximum temperature, humidity, Gross domestic product (GDP) per capita and registered unemployment among others.

3. Results and Discussion – Different alternatives of architectural elements composed of household waste that could be used, directly or with some modifications, as solar control devices have been identified. Similarly, alternatives of tensed structures and renewable energy systems that could be incorporated in them have been detected. At the same time, surveys to a representative sample of Spanish schools have proved that along with schools common economic problems, the satisfaction level from the solar control devices is also very low. Consequently, using household waste, which are low cost materials, to build these devices incorporating alternative energy systems and tensed structures could be a great novel opportunity to solve this aforementioned endemic problem. Additionally involving students and teachers in the construction process, designing of tensed structures composed of reused waste and low cost of devices is very positive for the educational process of the students. Moreover, this workshops are having a priceless awareness effect to children, teachers and their families about the household waste and solar problems of our Society. This is one of the main novelties of this research project.

4. Conclusions – As a conclusion, as it has been explained in the previous section, this project will contribute to reduce the environmental impact of Spanish schools and optimize their energy efficiency, comfort, environmental awareness and the learning process of its users. To sum up, the present research project, with this first part and its following parts, is expected to promote the awareness and better management of our Society present household waste generation while solving the endemic problem of Spanish schools solar control.

Appendix D.

Certificate of the published utility model of the waste-based solar control device.

GOBIERNO DE ESPAÑA MINISTERIO DE INDUSTRIA, COMERCIO Y TURISMO

Oficina Española de Patentes y Marcas

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Query date: 03/11/2022 01:08:04

Utility model U201831204(9) - MONTAJE DE CORTINA

Application No.: U201831204 **Filing date:** 30/07/2018

Publication number: ES1224335 **Publication date:** 04/02/2019 **Grant date:** 22/04/2019

Title: MONTAJE DE CORTINA

Status: Granted **Updated on:** 21/03/2022

Applicant / Owner:

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Country of residence:	ES ESPAÑA

Inventor:

Oriol Pons Valladares
Saeid Habibi
Diana Maritza Peña Villamil

Agent/Representative:

No agent/No representative

Classifications:

Invention IPC of patent application:	*A47H 1/18, A47H 23/08, A47H 23/02, A47H 1/00, E06B 9/24*
Invention IPC of granted patent:	*A47H 1/18, A47H 23/08, A47H 23/02, A47H 1/00, E06B 9/24*

Publication:

GOBIERNO DE ESPAÑA MINISTERIO DE INDUSTRIA, COMERCIO Y TURISMO

Oficina Española de Patentes y Marcas

c.e.o. Consulta de Expedientes OEPM

Publication number	Country of publication	Publication date	Document type
ES1224335	ES	04/02/2019	U Solicitud de modelo de utilidad
ES1224335	ES	26/04/2019	Y Modelo de utilidad

Processed according to law 24/2015

Event history:

Date	Text
30/07/2018	Registro Instancia de Solicitud
31/07/2018	Defectos en admisión a trámite tasa de solicitud
31/07/2018	1003U Notificación Defectos Admisión a Trámite
01/08/2018	3003_Registro Doc. Subsanación defectos en Admisión a Trámite Modelo Utilidad
01/08/2018	Admisión a Trámite
01/08/2018	1001U_Comunicación Admisión a Trámite
07/08/2018	Publicación Impago Tasa de IET de Modelo de Utilidad
03/12/2018	Realizado IET
05/12/2018	6109U_Comunicación Traslado del IET
20/12/2018	Suspenso en examen de oficio
20/12/2018	6101U_Notificación defectos en examen de oficio
28/12/2018	Publicación Defectos en examen de oficio
25/01/2019	3007_Registro contestación al suspenso en examen de oficio
28/01/2019	Continuación del Procedimiento y Publicación Solicitud
28/01/2019	1110U_Notificación Continuación del Procedimiento y Publicación Solicitud
04/02/2019	Publicación Solicitud
04/02/2019	Publicación Folleto Publicación
22/04/2019	Concesión
22/04/2019	1201U_Notificación Concesión
26/04/2019	Publicación Concesión Modelo Utilidad

Payments:

Date	Text
17/07/2018	Pago Tasas IET
09/09/2020	Pago 03 Anualidad
21/03/2022	Pago 04 Anualidad

Appendix E.

Certificate of the didactic support experience from CESIRE education center regarding workshops in schools with pupils.

Generalitat de Catalunya
Departament d'Educació
Centre de Recursos Pedagògics Específics de Suport a la Innovació i la Recerca Educativa

cesire*

En Julio D. Pérez Tudela, amb DNI 46053941Y, director del Centre de Recursos Pedagògics Específics de Suport a la Innovació i la Recerca Educativa (CESIRE) del Departament d'Educació de la Generalitat de Catalunya.

CERTIFICO: Que en Saeid Habibi, amb NIE Y5005767S, ha presentat els materials educatius "**Arquitectura escolar sostenible**" dins del marc de la formació "Amb TE de STEAM a primària", que va tenir lloc a la seu del CESIRE, el dia 26 de gener de 2020 de 18:30 h a 20:00 h.

I, perquè consti i tingui els efectes que correspongui, expedeixo aquest certificat a petició de la persona interessada.

Barcelona, 4 de març de 2020

Signat per JULIO DOMINGO PÉREZ TUDELA el dia 04/03/2020 amb un certificat emès per EC-Ciutadania

Julio D. Pérez Tudela
Director del CESIRE

Appendix F.

The presented and prototyped proposal of low-cost intelligent façade for the UPC Recircula challenge 2021.

PLANTILLA DE LA MEMÒRIA TÈCNICA DE LA SOLUCIÓ PROPOSADA.

RECIRCULA CHALLENGE 2021

SAMO Developers

April 2021

Recircula Challenge

INDEX

Recircula Challenge

Hub Recircula UPC AMB

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

A VIABILITAT DE LA PROPOSTA

A| VIABILITAT REAL DE LA PROPOSTA	

En aquest apartat s'ha de descriure la proposta i evidenciar la viabilitat real del model de negoci. Per a això, s'ha de proporcionar informació sobre la problemàtica i la deguda justificació sobre la seva viabilitat, tant econòmica com tècnica. Volem idees precises i clares.

A.1 IDENTIFICACIÓ DEL PROBLEMA, OBJECTIUS I SOLUCIÓ PROPOSADA

A.1.1 Identificació del problema: especifiqueu quina és la necessitat o problema que heu detectat. En la definició d'aquest problema o necessitat ha de quedar clar quin és el perfil de públic afectat per aquest problema ja siguin persones, empreses, organitzacions o altres col·lectius.
Informació de suport:

- *El model Canva us pot ajudar a planificar l'apartat A d'aquesta plantilla: públic objectiu, agents clau, identificació del problema, etc.* Link
- *Aporteu dades quantificables (p.ex. bases de dades, estadístiques, estimacions o altres). Podeu utilitzar annexos.*
- *Aporteu exemples o casos reals de la problemàtica o necessitat detectada.*

Negative impacts of existing buildings that require rehabilitation is increasing daily with dramatic consequences, chief of which are the environmental, psychological and financial problems [1]. In Spain, it has been reported that numerous buildings could not satisfy the current environmental, economic and social qualities and they are in urgent needs of rehabilitations. These quality flaws have affected buildings consumed energy, produced emissions and its inhabitants' comfort and their living quality mainly during the COVID-19 pandemic and lockdowns. Long list of researches resulted that a considerable rate of these buildings impacts can be improve by optimizing their façades. Adaptive façade is a pioneering technology in terms of optimizing energy consumption and comfort levels and reducing bills in buildings. However, their application in existing buildings has been lowly developed [2].

By growing the financial crisis in the world, long list of literatures has been investigated the adaptive façades from economic aspect to reduce their final production and maintenance costs. Correspondingly, the generated idea for this project also has special focus on the final production cost of adaptive façade while regulate buildings functioning, energy performance, bills, emissions and appearance attractiveness.

Early evidence on circular economy policies suggests the municipal solid waste as zero-cost alternatives which can be reused as modifiers composition of basic construction materials being foam glass and high-impact polystyrene wastes [3]. Reusing waste in construction while has economic contribution, can also contribute in reduction of environmental impacts. For instance, reusing blast furnace slags and pulverized fuel ashes can make a particular contribution in conserving energy in the manufacture of cementitious materials and of lightweight aggregates [4]. Moreover, reusing waste materials have social benefits for considered society as well. Pons et al, developed three prototypes of solar control devices for schools in Spain with the main tested and evaluated MSW materials in order to increase the pupil's knowledge about their future waste problems [5].

During the 2020, the COVID-19 pandemic has created enormous uncertainty to the world, and changed the profiles of solid waste management [6-8]. In Spain, which is the location for the numerical simulation of the present proposal, a late 2020 survey found moderate changes in waste stream quantities during the COVID-19 pandemic [9]. In the City of Barcelona, residents were advised to no longer put these new sorts of wastes being as personal hygiene/sanitary products, PP (Polypropylene) – see Annex A for abbreviations- face masks, PC (Polycarbonate) face shields and napkins in the organics bin but rather in the garbage One of the other main problems followed by

COVID-19 was the long-term lockdown and consequent inhabitants' emotional, intellectual, occupational, physical and well-being challenges inside the buildings. This problem originated mainly from these buildings required rehabilitations in terms of their lighting, ventilations, aesthetic comfort and living quality. Also, there are some quality flaws that also have influence on both energy consumption and emissions generation, which require rehabilitation specially in the core of their façades.
SAMO developers, considered these new sort of waste materials as an opportunity to develop novel waste-based low-cost adaptive façades for Spanish buildings in order to optimize their sustainability performance. This research project also aims to increase the society knowledge regarding global waste problems by a) collaborating with educational or health centers, and b) users' incorporation on the assembling process of the proposed façade system.

A.1.2 Definició dels objectius del projecte: en base als problemes especificats en l'apartat A.1.1, descriviu quins objectius us proposeu per solucionar els problemes plantejats en l'apartat anterior.
Informació de suport:
● *Definir quins són els objectius que voleu aconseguir amb el vostre projecte aplicant la tècnica M.A.R.T.E., és a dir, definir objectius Mesurables, Assolibles, Realistes, Temporals i Específics.*
● *El Model DAFO us pot ajudar a detectar debilitats a millorar i possibles avantatges de la vostra solució en base els objectius que us plantegeu. Link*

The main objective of the SAMO Developers proposals for Recircula Challenge 2021 is to design and develop a new low-cost, environmentally-friendly and user-friendly applicable adaptive façade technology for the refurbishment of existing architecture. This proposal has been developed considering all sustainability values: economic indicators from LCC phases, environmental indicators from LCA phases, and social indicators. This proposal aims to reduce the energy consumption and emissions generated in the usage of existing buildings as well as increase their inhabitants' well-beings and comfort by improving their a) natural lighting and b) natural ventilation while c) achieving socially accepted aesthetic results. This new developed proposal will contribute on the reduction of the generated COVID-19 waste materials by reusing an important amount of these materials.

A 1.3 Definició de la solució de producte o servei proposat: definir el producte i/o servei capaç d'aconseguir els objectius plantejats en l'apartat anterior especificant de quina manera s'aconsegueixen.
Informació de suport:
● *La proposta plantejada es pot basar en una solució no existent prèviament o en una millora d'una solució existent. En qualsevol dels dos casos, us heu d'assegurar que la solució o millora no existeix en el mercat.*
● *A més de la viabilitat tècnica i econòmica de la solució (que analitzareu en apartats posteriors) la innovació i la creativitat del vostre projecte són dos factors que us ajudaran en la cerca de solucions eficients que puguin marcar un factor diferencial respecte a solucions existents o similars.*
● *Material de suport: resum Manual d'Oslo sobre Innovació link (al final del web, podeu accedir al manual sencer en pdf)*

To achieve such objectives, the results of a previously developed new Multi-Criteria Decision Making (MCDM) tool have been followed in this research proposal [10].
This tool suggests that the generated façade for this proposal required to be: a) movable and adjustable considering user demands and weather fluctuations, b) has an acceptable level of U-value and insulation, c) able to provide view and natural light while avoid glares, d) able to direct wind to interior spaces and provide shading, e) flexible and aesthetically pleasant, f) possible to incorporate maximum waste materials, and g) effortless and quick to assemble and install.
The generated façade solution for overcoming the aforementioned problems in the Spanish architecture plus increased waste following COVID-19 pandemic, have been proposed for the first time. This novel façade technology can provide maximum lighting and thermal comfort, with the minimum assembling and installing costs.

By incorporating renewable energy systems and TiO_2 nano particles in these façade technology, buildings sustainability can also be optimized in terms of sequestrated carbon and energy conversion efficiency which is another novelty of this research project.
The other novelty of this proposal lies on the fact that it has been developed completely with COVID-based waste items and has very simple and safe assembling process which can be used as a utility model for the residents or staff and even students. This way of sustainability rehabilitation with waste materials will have preventing influences by increasing users' knowledge and awareness about the global waste challenges.
Regarding aesthetic values, the design team has proposed multi-dimensional geometry incorporating low-voltage multi-chip LED arrays lights which will provide fascinating night visions for users and pedestrians.
In addition, this proposal for the first time investigates the mechanical behaviors of the several sorts of the COVID-19 waste materials to have minimum toxicity and maximum resistance.

A.2 TREBALL EN XARXA AMB AGENTS CLAU

En aquest apartat s'ha d'analitzar quina és la xarxa d'actors clau de la proposta, tant les aliances que necessitem per concretar el model i enfortir-lo com l'orientació a l'usuari en relació als actors afectats o públic potencial. És un factor de gran importància i en la majoria dels casos determina la rendibilitat del model de negoci i l'impacte en la societat.

Informació de suport:

- *Expliqueu com es pot dur a terme la proposta amb el actors relacionats.*
- *Interactueu amb la xarxa d'actors incorporant-los en el procés.*
- *Podeu utilitzar eines d'anàlisi d'actors,entrevistes, enquestes.*

This research proposal is part of one of SAMO developers members' PhD research thesis, which develops low-cost intelligent facade from waste materials to enjoy the wide range of their advantages in all rehabilitation-required architecture. Until know different real-scale prototypes of waste-based façades have been developed for schools in Barcelona, Spain to increase pupil's knowledge and rehabilitate schools with lowest possible costs. The following presents the, networks and the target community.

Collection:
SAMO developers have succeed to collect COVID-19 waste materials through innovative approaches from encourage people in social medias to agreements with different centers. As first steps, a poster has been shared in Facebook and Instagram to collect the COVID-19 waste items as much as possible which it had also educational influences for the viewers and mostly have incorporated in their classes (See Annex B). As previous experiences, we also have succeeded to present our idea to different centers. For example, in Iranian schools and health centers. These two processes of collecting the waste materials helped us to a) research around how COVID-19 waste materials can be collected, and b) analyze the acceptability of rehabilitating the building façades with COVID-19 idea in society. Figure 1 resenting the collected waste items by pupils in Sweet Baby primary school in Tabriz, Iran.

Figure 1. The collected waste in school and pupil's collaboration.

Classification:
Waste items have been collected based on a) certain safety protocols (see section A3.2.2), b) mechanical characteristics (see section A3.2.3), and c) design configuration. Accordingly, two types of PP face masks and different types of PET sanitizer bottles have been considered as qualified material for this research proposal. These considered items have been already explained in detail to the involved schools, health centers and in the social media, as previously explained. Therefore, the collected waste materials have been adapted to the needs of SAMO developers and will be used during the prototypes production.

Marketing:

The key strategies in the marketing of this proposal are two-folded:
a) DIY association: during the first steps of this project, this proposal will be shared with the intellectual protection of a utility model and the aid of booklets and manuals by collaborating NGOs. This utility model will be part of the Do-it-Yourself social movement, so that freelances and organizations will be expected to be incorporated from all around the world. This concept will be provided freely to different social medias and websites such as our previously developed webpage (https://sites.google.com/view/arqescsost/) which targeting educational centers rehabilitations and increased learning performances.
b) Promotion: In this case, SAMO developer's proposal will be offered to different possible private and public organizations and institutions after analyzing the market demand without limiting the geographical locations and target audiences from children to aged generations. However, future investigations and surveys will be done to characterize its influences on different range of societies with different ages or cultures. Expected interested institutions are: the department of education, institutions responsible of public housing provision, institutions responsible of waste management.

A.3 DISSENY, QUALITAT I VIABILITAT TÈCNICA

A 3.1 Metodologia proposada per aconseguir els objectius: és el mòdul on es presenta quins són els passos que s'han seguit per a dur a terme la idea presentada. És important que les accions siguin clares, ja que descriuen COM s'aconsegueixen els objectius.
Informació de suport:
- *Descriure quins són els passos a seguir per a dur a terme el projecte.*

This research project has followed the 3 phases presented in Figure 2. The first phase, has started to identify the problems as explained in previous sections. The second step of first phase has reported the results of previously developed new MIVES sustainability assessment tool. This new MIVES, assessed the sustainability of five outstanding intelligent façade systems and has selected the most sustainable alternatives and technologies and has been provided suggestions and recommendations for future intelligent façades. This assessment has been done considering all three pillars of sustainability and 16 indictors (see Annex C) [10]. This model and its outputs helped SAMO Developers to generate their solution for recognized problems as the third step of first phase. Moreover, this study evaluates the degradation behavior of possible types of COVID-19 waste items

The second phase has generated a new façade technology optimized for the specific problems of Spanish buildings in three steps. The first step searches possible COVID-19 waste items considering various parameters and their aging and mechanical behavior tests. These tests consisted in exposing samples of COVID-19 wastes to natural weathering in a representative location of the application of this research project plus in the experimental prototyping position. The representative site was within Barcelona metropolitan area, Spain, a Mediterranean region with an annual average radiation dose of 4.3 kWh/m^2 [12]. The experimental site was in Tabriz, Iran, (38.0962°N, 46.2738°E).
Steps 2 and 3 have been developed the first theoretical concept, its first 3D model and first experimental prototype. These steps are using Rhinoceros® and its Grasshopper® plug-in, Autodesk Revit® and Autodesk 3ds Max® to analyze the technical features and operational performances of the concept. The experimental prototype has been developed on the external south façade of a typical flat in aforementioned experimental site Tabriz, Iran.

The third phase, evaluates the economic, environmental, social and technical performance of the prototyped and modeled concept. In this phase the feasibility and viability of the concept will be evaluated as well. The concept will be evaluated based on 16 indicators of the new MIVES model, LCC and LCA calculation approaches and numerical tests. During the numerical tests, a room modelled in Revit which was a typical, south-facing perimeter office located in Barcelona, Spain. As the next step, the global sustainability index of the concept is reported. As the final step, will carry out a sensitivity analysis in order to prove the robustness of this research study.
Figure 2 presents this proposal main phases and following steps.

Phase 1 Prepare	a) Define the problem b) Define the solution
Phase 2 Develope	a) mechanical and aging tests of materials b) Numerical simulations c) Experimental prototype
Phase 3 Evaluate	a) Partial sustainability index b) Global sustainability index c) Sensitivity analysis
Phase 4 Implement	a) Pilot implementation b) Generalized implementation in Tabirz and Barcelona c) Implementation in other cities & countries

Figure 2. The main phases and following steps of the proposal.

A 3.2.1 Disseny: descripció del disseny del producte o servei. El disseny es considera tant la descripció gràfica del producte o servei con els seus fonaments, això és, dimensions, formes i les toleràncies, així com informació del material que s'utilitza.
Informació de suport:
- *Descriure el disseny de la solució.*

- *Descripció del procés del producte o servei, per exemple mitjançant un diagrama de flux.*
- *Recomanem la utilització d'annexos si disposeu d'imatges dels prototips, renders, assajos o altres.*

Design: The concept features a dynamic shading system consisting of individually movable tiles. The modules are confined to a predetermined geometry inspired by AL-Bahar tower Mashrabiyah façade which has been scored as the most sustainable façade in the MIVES. The design process has been started by developing a 3D model by Rhinoceros® to analyze the operation and movement patterns. Figure 4 shows some views and details of this model. In this design, the shell consists of two 100 x 100 cm rectangle modules, which operate as a kinetic external layer, sitting 50 cm outside the main façade on an independent structure. Each module is sub-divided into eight triangular frames.

The tiles can be raised and folded manually for various functions such as shading, solar gains, daylight distribution, energy saving or energy generation.
Considering the final production cost of the proposal, the main structure, supporting frames, filling materials have been developed by incorporating COVID19-based waste materials. Except Cantilever struts which are stainless steel fixed to the main structure of the building to support the dynamic units. By evaluating mechanical and aging behaviors of COVID-19 waste materials, PP face masks, PC face shields and PET sanitizer containers have been qualified for developing this concept. Moreover, the structure and frames will be arranged by low-voltage multi-chip LED arrays lights which will shine during the nights. Table 1 presents the total amount of waste items among other components used for the 1m^2 of the proposed façade system.

COMPONENT	MATERIAL	QUANTITY
Face mask	PP	30 unit/m^2
Sanitizer bottle	PET	60 unit/m^2
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	2.48 kg/m^2
Cover	TiO_2	0.4 kg/m^2
Connections	Twist ties	1m/m^2
Lighting	5V LED multi-chip LED	8m/m^2

Table 1. the total waste items and components used for the proposed façade system.

Production: The process is starting by transforming the PET container and PC face shields into a structural piece that, together with screws and bolts makes it a very resistant structure. As shown in Figure 4 containers are cut at both ends creating a plastic sheet and rolled into a much more compact and resistant tube. The structure and frames can be developed by joining several of these tubes by drilling and bolting them together. The angled connections of tubes are made with the caps of the bottles and the bases of the bottles, together with the help of some bolts which makes star connections. Once we have the main element, three of them has to be joined by twist ties inside face masks, forming a 50 x 50 cm scalene triangular shapes. The frames of this triangular shape will be filled by LED arrays without using any connections which can be disassembled easily for future uses. This concept uses PP face masks as a solution for closing the module as they block glare while transferring light and protect building from wind and water pass as they has low moisture-absorption rate. These face masks will be connected to each triangle tubes by their own threads. Once the triangles have been assembled, the module is assembled by joining eight triangles with others using the same face mask twist ties. At the end, all components will be covered with TiO_2 nanomaterials referring its proven features in previously carried out study [11]. As presented the introduced assembling process is considerably simple while used materials are safe to be used. Figure 3 presents the modules key components and connections which their assembling process have been illustrated in Figures 4 and 5.

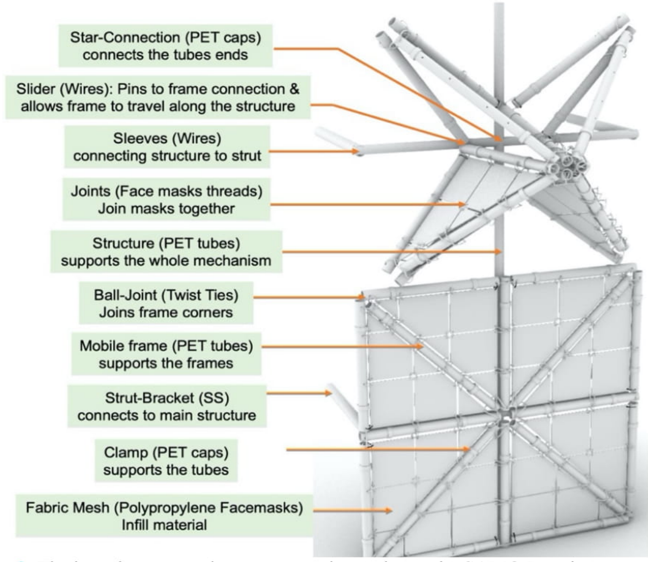


Figure 3. The key elements and components that make up the SAMO Developers proposal

Figure 4. Assembling process of the proposal

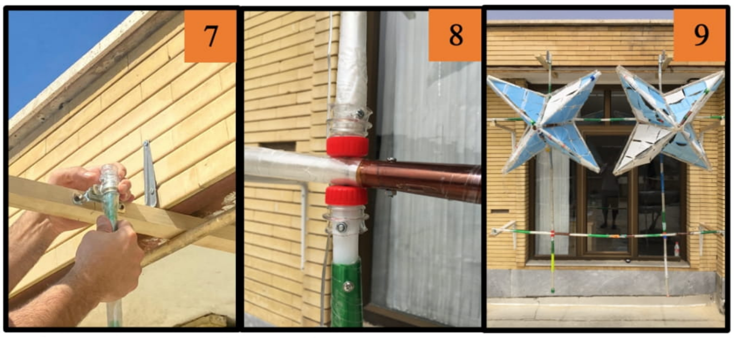


Figure 5. Assembling process of the proposal

Our first full-scale proof of concept prototype, shown in Figures 6. The SAMO Developers prototype is 2x2 m and contains 32 individually modules. The prototype has been developed for a typical room in Tabriz, Iran with the daily average main conditions of: irradiation from 15.27 MJ/m^2, rainfall 79.7mm, temperature from -11 to 38 ◦C and with an average relative humidity of 74%. The dimensions of selected room are 4.8x3m with WWR of 30% and U-value equal to 1,6 W/m²K. To monitor the thermal comfort, temperature, humidity and illuminance sensors have been deployed inside the room in both before and after application of the prototype. As the future steps, feedback from the occupants will also be gathered through behavioral studies. The façade has been fabricated and assembled in 55 hours using minimum use of machinery and equipment.

Figure 6. a) The day view of the first developed prototype, b) The night view of the first developed prototype.

A 3.2.2 Qualitat: volem propostes específiques relacionades amb el producte/serveis i la seva qualitat, això és, l'adequació a l'ús. La qualitat recull els requisits que ha de complir el producte / servei, tant funcional com estètic i les degudes normes de compliment i funcionament.

Informació de suport:

- *Es valorarà que les propostes (producte o servei) i la seva qualitat siguin específiques.*
- *En l'edició Recircula Challenge 2021 cal tenir en compte les normes i recomanacions associades a la Covid-19.*

This section details the quality considerations for the SAMO developers' concept. The current design has three key elements: 1) shading panel consisting of 8 scalene triangle modules, 2) supporting structure, and 3) connection slider between structure and panel. All these elements are made of COVID-19 waste items and connection bolts.

Technical performance: dynamic panels are supported by stainless-steel strut-bracket arms 700 mm from the frame of the building. This offset enables the panels to attain a fully open and fully closed positions without interfering with the structure. In addition, it provides a thermal buffer zone, solar preheating of ventilation air, energy saving, sound protection, wind and pollutants protection, night cooling and space for energy collection devices like VAWT (Vertical Axis Wind Turbines). The innovative structure is made by rolling the PET bottles and making 1-inch tubes which have the required strength and stiffness. Moreover, the concept has acceptable level of reaction against wind and rain water which makes this solution to be used as other applications like areas that have suffered natural disasters, together with a covering, so that the space is habitable. In addition, the LED strips have been arranged inside the PET tubes and are technically and electrically protected. The structure and shell have the weight of 1.8kg/m^2 which were designed to withstand an approximated wind load of 100N/m^2 (corresponding to a windspeed of E70 km/h). Although, wind-loads may cause horizontal movements up to ± 100 mm. The system is restricted from any vertical movements and are absorbed by the flexibility of the structural frame.

Safety: In this proposal, the users of buildings are the main contributors of its assembling and installing process. Accordingly, SAMO Developers have considered three levels of safety protocols and precautions for this proposal to provide maximum safety for all participants.

The first level of protocols considers user safety against COVID-19 virus spread in accordance with legal guidelines. This protocol suggests that the collection of waste items should be done with gloves and face masks. Moreover, it suggests that the collected materials they should be quarantined for a minimum of 72 hours to protect assembling members.

The second safety protocol level is protecting members from probable damages or injuries during the assembling and installing process. This protocol suggests: a) use of highly safe and reliable tools, b) minimum use of risky and sharp wrenches, c) use of bolts and nuts instead of risky adhesives or welding, and d) regularly wash hands with an alcohol-based hand rub or clean them with soap and water.

The third safety protocol level protects buildings users and pedestrians from the damages which can occur after assembling the façade, such as disporting, rupture or possible falling of parts. This protocol suggests maximum wind load bearing and fire resistance previsions during design and material selection process.

Accordingly, several safe, major and disinfect-able COVID19-based waste items have been studied regarding their mechanical and degradation properties in the following sections. These safety protocols will be provided to the users and urge to clearly follow these precautions before intending to implement the proposed façade system.
]

A 3.2.3 Viabilitat tècnica: s'ha de demostrar la viabilitat tecnològica per a generar una solució/producte innovadora. Entenem que és viable tecnològicament quan existeix tecnologia que és capaç de produir el disseny especificat complint amb la qualitat requerida. Per a això s'haurà d'aportar informació sobre la maduresa de la tecnologia que s'utilitzarà.

Informació de suport:

- *Es valorarà que la viabilitat tecnològica estigui justificada amb evidències.*
- *Es valorarà la innovació de la tecnologia utilitzada.*

This proposal feasibility relies on the appropriate durability and fire properties of its materials, which satisfy the design requirements for the aforementioned market and case studies that the proposal aims to satisfy. The required durability of this research proposal is considered to responds to the 1-year duration for the Spanish architecture. This level of durability has been reported as eligible material for façade development relying on the previously obtained results that exclusively studied one-year weathering and laboratory aging behaviour and mechanical performance of household waste components [11]. The reports showing that the tensile strength of the used waste materials composed decreased due to the UV aging. Moreover, these materials are approved to be used in the exterior conditions as well as the main joints and stapled joints. Furthermore, a service life of 10 years for non-structural parts of the proposal is expected specially by applying TiO_2-based paint containing Disperlith foodgrade Elastic treated with Disperlith Primer which achieved the highest durability performance. After this year, the 97% of the concept can be reused if they maintain the required properties or otherwise recycled by a second processing cycle.

The aging test of PP face masks and PC face shields has been caried out in natural weathering from December 2020 to April 2021. While the mechanical and aging test of PET containers, thread joint and twist ties joints have been evaluated in previous research study on various items of MSW items from 2017 to 2020.

This test consisted in exposing samples of a) PP face masks and b) PC face shields to natural weathering in a representative location of the application of this research project plus in the prototyping position (see section A3.1). The both tests carried out during five months and will evaluate till 12 months, which is the aforementioned aimed durability of the project. Table 2 present the results of the natural weathering aging tests as well as images of the original and aged samples. The images are showing that these tests degraded the studied samples which were involved: a) sheet separation and distortion in PP face masks; b) yellowing of the both sample types.

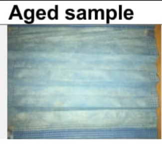
Component	Material	Test time	Shsp	Sw	Dist	Yell	New sample	Aged sample
Face mask	PP	5mo	4mo	-	5mo	4mo		
Face shields	PET	5mo	-	-	-	5mo		

Table 2. Main results of the natural weathering aging tests.

Legend: mo: months; ShSp: sheets separated; Sw: swelling; Dist: distortion; Yell: yellowing.

The fire properties of the selected waste materials have been reported in the literature. As shown in Table 3, these COVID-19 waste items have a poor behaviour exposed to fire as other synthetic polymers and shouldn't be exposed with fire. Considering their TTI, PP face masks has the lower coefficient followed by PET.

Component	Material	TTI (s)	References
Face mask	PP	23	[13]
Face shields	PET	40	[14]

Table 3. Fire properties of selected covid-19 waste materials.

Legend: Time to Ignition (TTI), Total Heat Emitted (THE).

Accordingly, the analysis and tests resulted that the studied materials are good façade components. Moreover, the concept it is robust, lightweight, and is designed to resist the following:
• High exposure to UV solar rays and atmosphere temperatures reaching up to 49 degrees.
• Humidity reaching up to 100% during summer.
• Corrosion – if the building faces the sea or exposed to high levels of sand and dust.
• High wind-loads and wind speeds up to 100N/m^2 and 70 km/h respectively.
• Fire up to 1 hours for the main supporting frame, as it is comprised of steel components.

B| IMPACTES	SOCIALS AMBIENTALS ECONÒMICS

L'objectiu és que compartiu la visió sostenible global de la vostra proposta. Per a això, heu d'explicar com la idea i el model proposat poden fomentar tant l'economia circular, com la inclusió i la responsabilitat social. S'avaluen els resultats socials, ambientals i econòmics del projecte.

Podeu utilitzar aquesta guia orientativa en economia circular per a fer un autodiagnòstic del vostre projecte i assegurar la circularitat de la vostra proposta.

Com els criteris han de ser fàcils d'usar tant per als dissenyadors del projecte com per als avaluadors d'aquesta, s'han classificat els resultats de la següent manera:

- Els resultats socials han de ser una estimació de la repercussió del projecte en els aspectes d'índole social. S'haurà d'argumentar el raonament dels resultats exposats.

- Els impactes ambientals es reporten mitjançant una taula amb indicadors per a mesurar el consum de recursos i la circularitat dels projectes. L'estimació de les mètriques que es proposen han d'estar ben argumentades.

- Finalment, s'haurà d'evidenciar els resultats econòmics que s'esperen del projecte. Es proposen una sèrie d'eines són molt necessàries en el món dels negocis, i que serveixen per a mesurar la rendibilitat de la proposta.

B.1 IMPACTE SOCIAL: RESPONSABILITAT SOCIAL, INCLUSIÓ I IMPACTE A LA SOCIETAT

Les iniciatives d'Economia Social i Solidària estan presents en tots els sectors de l'activitat econòmica, des de l'energia fins a la cultura o l'alimentació. Plantegeu propostes i iniciatives en relació al vostre projecte que contribueixin a l'Economia Social i Solidària.

Informació de suport:

L'Economia Social i Solidària és el conjunt d'iniciatives socioeconòmiques, formals o informals, individuals o col·lectives, que prioritzen la satisfacció de les necessitats de les persones per sobre del lucre.

- *Guia pràctica sobre Economia social i solidària* aquí
- *Portal web de La Xarxa d'Economia Solidària (XES):* link
- *Pla d'impuls de la XES de l'Ajuntament de Barcelona:* link

The social impacts of this proposal have been assessed based on the social indicators from MIVES requirements tree (see Annex C). These indicators analyze the values that this proposal can provide to users during its production and using phases; these include safety values, construction values, appearance and different dimensions of comfort levels. These indicators analyze the partial social sustainability of developed façade concept and each one has measurable variables from 0-10 that have been used to quantify this new proposal. The following paragraphs detail this proposal social impacts based on these five indicators.

a) **Fabrication and assembling easiness:** this indicator evaluates the production and assembling ease depending on a system being low-tech or high-tech, plus its simplicity. Adaptive façade technologies often involve innovative technologies, resulting in challenging projects with relatively high risks. Project developers tend to take conservative attitudes to adopt this type of new technology because the risks are associated with chances for disproportionate fabrication and assembling time and required highly professional experts to design, analyze and develop. The proposed façade concept has been planned to develop by users in order to reduce costs and increase their knowledge on global waste problems.
The designed geometry avoids major twisting, bending and stretching of components while going from one opening configuration to another. The designed structure as well, is quite simple and has clear assembling process which can be fabricated by all ages from children to aged generations. In addition, the design process has considered the risks of rattling and vibration during use phases and achieved the minimum required maintenance specially in high levels. Thanks to the lightweight structure and materials used in the concept, the need for scaffolding and large cranes has been eliminated and the process is comparatively effortless. The application of TiO^2 cover was assumed to be done with a roller resulting in no losses during the application.

b) **Flexibility:** evaluates the flexibility of the proposed façade system and repercussion of it in the rental price considering the novelty of the systems, appearance, reliability, and acceptancy. The proposed system is able to continuously adapt its layout to evolving environmental needs. By considering the economic indicators, the proposed façade can operate by manual devices and provides value to user by their interaction to adapt their environment to their own requirements and increase the acceptancy of proposal. In addition, it turned into resistance and reliable options as well, if has been produced with attention and precision. The proposed flexible façade also is able to increase the property value by provided aesthetic option. TiO_2 is a silver-white metallic element which its application provides a good strength and excellent corrosion resistance for façade.

c) **Ventilation performance:** assesses orientation and movements of the façade components in line with passive transferring of the wind direction into spaces and provided fresh air and natural ventilation. Architects typically choose natural ventilation to provide the maximum comfort hours for users, reduce emissions and reduce energy consumption. The proposed concept has good level of the ventilation performance by provided passive ventilation and contaminants sequestration. The façade acts as a DSF (Double Skin Façade) system with the predicted 50cm space between the main façade of building and new layer which can provide natural ventilation about 60% of the year. This ventilation among applied TiO_2 cover can considerably improve the air quality in interior spaces. Moreover, the relative humidity has been predicted to decline up to 15%.

d) **Lighting performance:** A well-designed façade can enhance the daylighting performance by regulating solar radiations and glare. By responding dynamically to the changing environmental context, the proposed façade system has a major impact on the amount of natural daylight admitted into the building and reduces the cooling loads required for air-conditioning. SAMO developers investigate the potential impact of the proposal on the daylighting performance of building façades through the selection of the optical properties. The study focuses on perimeter offices in the Mediterranean region in Barcelona, Spain. A room modelled in Rhinoceros® which was a typical, south-facing perimeter office located in Barcelona, Spain (latitude 43.7°N). The three-section façade concept was applied with Window-to-Wall ratio of 50%. The office dimensions are 4m (width) x 5m (depth) x 3.2m (height). Three different configurations of the proposed concept were simulated: 10%, 50% and 100% (Figures 7). The minimum value of 10% was selected in order to ensure a minimum view to the outdoors. For this study, the continuous Daylight Autonomy (cDA) [16], and the spatial Daylight Autonomy (sDA) [15] metrics are used to evaluate the annual daylighting/lighting performance during the 1827 occupied hours (8:00 to 18:00).

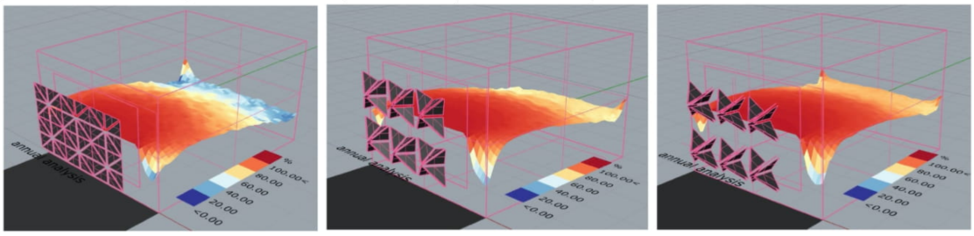


Figure 7. The annual analysis of capital Daylight Autonomy in three different configurations as a) 10% visibility, b) 50% visibility, and c) 90% visibility.

Annual cDA are presented, for the center line of the office, as the percentage of occupied hours where the minimum work plane illuminance levels of 300 lx are met. Annual sDA are presented as a percentage of the entire office workplane where the minimum workplane illuminance levels of 300 lx (sDA300lx/50%) are met for 50% of the occupied hours. All of the simulation results are presented in Figure 8 as a function of the visible effective transmittance of the proposed façade.

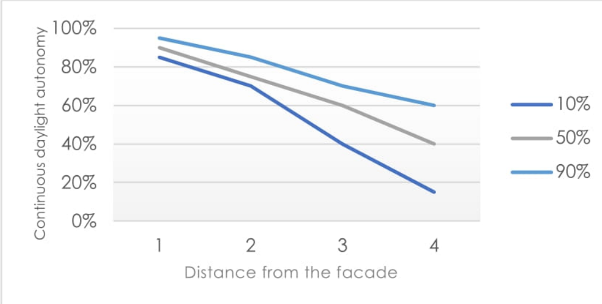


Figure 8. The annual continuous Daylight Autonomy in three configurations.

As shown the design team have been successfully admit natural diffused light into the building and maintain a useful daylight throughout daily working hours (08:00 am to 18:00 pm) with the PP face masks light transmission co-efficient of 20% [17]. After application of the real-scale concept, light sensors located at the perimeter of the ceiling in different distances read average of 450lux and maintained the required comfort. Moreover, other benefits include increased visibility and privacy, a unique and iconic aesthetic, and overall quantitative and qualitative improvements have been achieved after application. As shown in Figure 9, the concept also reduces solar glare, while providing better visibility by avoiding dark tinted glass and internal blinds that distort the appearance of the surrounding view.

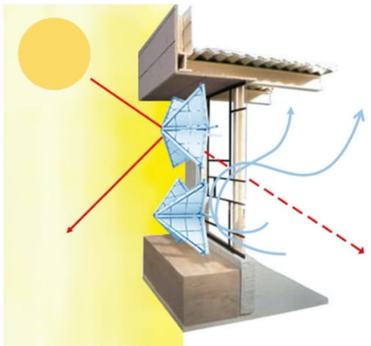


Figure 9. The different effect of the proposed façade in terms of visibility, admission of natural light and overall working space quality.

Table 4 presents the total light performance of the proposed façade system in both before and after application scenarios which done by numerical and experimental simulations.

Value	Coefficient before application	Coefficient after application	Simulation model
Illuminance	2600 Lux in 75%of the office	300 Lux in 75%of the office	Numerical + Experimental
Light transmission	100%	20%	Literature
UV light-filtering	55% by tempered glass	75% (2mm PP layer + Tempered glass)	Literature
Improved daylight	NA	70–150%	Numerical + Experimental
View	100%	80%	Numerical + Experimental

Table 4. The light performance of proposed façade before and after application.

e) **User safety:** Design for safety is still in a nascent stage which is a growing demand for it in terms of fire resistance, toxicity and user wellness among the decision-makers in the construction industry, particularly pertaining to the façade. SAMO Developers by taking into account different safety considerations they have been avoided from these risks. According to the aforementioned fire tests references for PET and PP [14] all these household waste containers have a poor behavior exposed to fire. At temperature above 100 °C polypropylene dissolves in aromatic hydrocarbons, such as benzene and toluene [18]. On the other hand, application of TiO_2 has the most positive impact on the environment and human Health by decomposing harmful organic compounds, killing bacteria and eliminating odors. However, producers suggests that TiO_2 should be applied on surfaces with great care.

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B.2 IMPACTE AMBIENTAL: CIRCULARITAT, VISIÓ SISTÈMICA I EFICIÈNCIA EN L'ÚS DELS RECURSOS

Expliqueu les millores en el context de l'economia circular. Heu de calcular les millores en relació a l'ús de recursos, energia i ocupació verda així com descriure quina estratègia d'economia circular segueix el model que es presenteu.

Informació de suport:

- *Avaluació de les millores del projecte en termes de recursos i energia.*
- *Explicació de l'estratègia de l'economia circular que s'aplica.*
- *Mesurar els indicadors que es proposen per a quantificar com de circular és el projecte i quins impactes ambientals té.*

This research proposal in all LCA phases has evaluated potential impacts of production, transportation, assembling, use and waste management of the developed façade concept. This assessment has been carried out following previous MIVES model in three levels as fabrication phase, use phase and end of life phase and based on six indicators as a) Embodied energy, b) Embodied carbon, c) Annual energy saving, d) Energy conversion efficiency, e) Sequestrated carbon and f) Recyclability. This proposal also assessed all suggested indicators of this template as material qualities and durability.

a) **Embodied energy:** assesses the amount of energy required in two phases of fabricating and assembling of the proposed façade in KWh/m^2. As mentioned before, one square meter of the concept has been assembled using 30 PP face masks (17x19cm), 60 PET sanitizer bottles (28x8cm), 1 stainless steel strut bracket pipe (70x4cm), and finally 0.4litre of TiO_2 cover. Except drilling bottles, the whole assembling process is done by manual devices without using electricity. The used machine is a small size 50/60HZ drilling machine with the rate of 6bottle/minute which accounted for less than 0.01% of the whole life cycle. Table 5 presents that the consumed energy for each square meter of proposed façade is 104.41 kWh, which 40% of this energy has been saved by reusing face masks and bottles.

Component	Material	Embodied energy	Quantity	Value	References
Face mask	PP	0.01-0.03 kWh/unit	30 unit/m^2	0.3-0.9 kWh/m^2	[19]
Sanitizer bottle	PET	0.58 kWh/unit	60 unit/m^2	34.8 kWh/m^2	[20]
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	22.91 kWh/kg	2.48 kg/m^2	56.81 kWh/m^2	[21]
Cover	TiO_2	30.5 kWh/kg	0.4 kg/m^2	12.2 kWh/m^2	[22]
Multi-chip led	PCB Silicon	Not available	8m/m^2	Not available	-
Total EE per each square meter				**104.41 kWh/m^2**	

Table 5. The total embodied energy of the proposed façade.

b) **Embodied carbon:** considers CO_2 emissions during production and assembling phase. Table 6 presents these values for SAMO Developers concept in detail. The total amount of EE for each square meter of the proposed concept is 19.46 $kgCO_2$ which stainless steel production has the most environmental impacts. However, this amount can be recovered during the first 3 months of use.

Component	Material	Embodied carbon	Quantity	Value	References
Face mask	PP	59 gCO_2-eq/unit	30 unit/m^2	1.77 $kgCO_2/m^2$	[19]
Sanitizer bottle	PET	58 gCO_2-eq/unit	60 unit/m^2	3.48 $kgCO_2/m^2$	[20]
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	4.53 kg CO_2/kg	2.48 kg/m^2	11.23 $kgCO_2/m^2$	[21]
Cover	TiO_2	7.47 $kgCO_2$/kg	0.4 kg/m^2	2.98 $kgCO_2/m^2$	[22]
Multi-chip led	PCB Silicon	Not available	8m/m^2	Not available	-
Total EC per each square meter				**19.46 $kgCO_2/m^2$**	

Table 6. The total embodied carbon of the proposed façade.

c) **Energy saving:** measures the amount of energy that can be saved in kWh/m^2 facade. This indicator analyzes the U-value and ability on controlling solar radiation and heat during summer and winter and resulted saved energy by cooling and heating systems. The U-value can be obtained according to Equation (1) [23].

$$U = 1/Rt \quad \text{Equation (1)}$$

Where Rt is the total Thermal Resistance of the element composed of layers (m2K/W) and can be obtained according to Equation (2).

$$Rt = Rsi + R1 + ... + Rn + Rse \quad \text{Equation (2)}$$

Where Rsi is Interior Surface Thermal Resistance, Rse is exterior surface Thermal Resistance, and R1, is Thermal Resistance of each layer which is obtained according to Equation (3).

$$R = D / \lambda. \quad \text{Equation (3)}$$

Where D is material thickness (m) and λ = Thermal Conductivity of the material (W/Km). By considering the thickness of 0.003 and the K-value (thermal conductivity) of 0.11W/Km and density of $0.85g/m^3$ for pp face masks [24], the U-value of the proposed façade has been resulted as 5.069 W/m^2K.
Furthermore, the research studies around Al-Bahar tower façade, confirms that Mashrabiyah geometries and its movement patterns can reduce Heat by 20%, provide shading effect by 80% and the total energy saving by 20% from lighting and 40% from heating and cooling [25].
By taking into account the obtained U-value and light transmission co-efficient of 20% [19] for PP face masks (as filling material) and added TiO_2 cover, the total energy saving of 15% for lighting and 25% from heating and cooling has been calculated.

d) **Energy conversion efficiency:** the ratio between the useful output and input energy of the proposed façade during the usage phase is the energy conversion efficiency. This ratio can be negative, neutral or positive is depending on the used energy by sensors or mechanical equipment, and the generated heat and/or electrical energy in an intelligent facade technology. This research proposal in the future steps will integrate the green energies in its proposals being as application of PV tiles or small-scale wind turbines to produce the part of required energy for the building. By the way, this rate for the proposed façade system is -1.2% due to consumed 120 watts of energy by multichip LED arrays in 1 square meter.

e) Annual sequestered emission: Proposed façade system can contribute on CO_2 reduction in two methods as a) absorbing emission and b) reducing consumed energy. The amount of CO_2 reduction by façade system will depend on the design, the available façade area, the height of the building, and the climate conditions at that particular site. Based on previously done MIVES assessment, the use of Photocatalytic TiO_2 paints will actively contribute to the absorption of chemical pollutants 0.26 $g/day/m^2$ [10]. Moreover, the contribution of facade on energy saving of the Building results 0.47 TCO_2/year by used mechanisms. Accordingly, 0.48 TCO_2 Can be sequestrated by 1 square meter of the proposed façade system in each year.

f) **Recyclability:** recycling of demolished wastes can either help relieve the landfill capacity and energy from existing building materials. However, recycling of COVID-19 waste items is a challenging process and authorities in many countries have been agreed to dispose them instead of recycling to reduce the virus spread. Although there is a lot of social activities and companies have been raised to criticize the global waste problems of COVID-19. TerraCycle® company, recently have been developed Zero-Waste-Boxes for health centers and they collect and recycle the dominant PPE wastes of COVID-19. As an example, they have densifying the polypropylene-dominant mixture from the face mask into a crumb-like raw material that's used in plastic lumber and composite decking applications. Or the elastane or rubber band portion is ground into a fine mesh regrind and mixed with recycled plastics as an additive to provide flexibility and malleability to products. In Addition, gloves are processed into a rubberized powder which is used for flooring tiles, playground surface covers and even athletic fields [26]. Table 7 presents the 94% recyclability rate of proposed façade and detailed components recyclability in End-Of-Life phase.

Component	Material	Recyclability	Quantity	Debris	References
Face mask	PP	95%	30 unit*3.5g/m^2	6 g/m^2	[27]
Sanitizer bottle	PET	100%	60 unit*68g/m^2	Zero	[28]
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	100%	2.48 kg/m^2	Zero	[29]
Cover	TiO_2	0%	0.4 kg/m^2	400g/m^2	-
Multi-chip led	PCB Silicon	90%	0.3kg/m^2	30g/m^2	[30]
Total debris per each square meter				**436g/m^2**	

Table 7. recyclability of the proposed concept and it's all components

d) **Reusability**: In this research proposal, the practice of dry connections with bolts and nuts and making them visible, allows materials to be easily, cost-effectively and rapidly taken apart and directed for further reuse as shown in Table 8. Reusing of material is practically new in construction sector which is replacing with recycling in near future and needs more researches around.

Component	Material	Recyclability	Quantity	Reusability
Face mask	PP	0%	30 unit*3.5g/m^2	0%
Sanitizer bottle	PET	100%	60 unit*68g/m^2	100%
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	100%	2.48 kg/m^2	100%
Cover	TiO_2	0%	0.4 kg/m^2	0%
Multi-chip led	PCB Silicon	100%	0.3kg/m^2	100%
Reusability of 1 square meter				**97%**

Table 8. Reusability of the proposed concept and it's all components

SAMO developers for further observations, they have been assessed the environmental impacts of the proposed façade based on t the suggested indicators of this template. Table 9 presents additional information around the environmental performance of the proposed façade system. The total weight of the proposed façade has been calculated as 7,06kg/m^2 including 2,48kg/m^2 of Strut-Bracket, 4,08kg/m^2 PET bottles, 0,1kg/m^2 PP face masks and 0,4kg/m^2 TiO_2 cover. As shown the considered durability of 1 year for the concept has been satisfied in all components which TiO_2 cover for facemasks have been increased its resistance and durability up to 50%. However, Tio2 application requires precautions to avoid probable respiratory allergies as be classed as a category 2 under REACH Regulation [31]. In addition, the cover to keep its performance need to be renewed after 3 years [28].

Component	Description	Face-mask	PET bottle	Strut-bracket	Cover	Concept
Durability	Service life	2 years	20 years	50years	3 years	2 years
	Improved service	50%	NA	NA	NA	20%
Material flow	Raw material	Zero	Zero	Zero	100%	5%
	Recycled raw material	Zero	90%	90%	Zero	83%
	Recycled material in concept production	100%	100%	Zero	Zero	92%
	End-Of-Life Recycle	100%	100%	Zero	Zero	95%
	End-Of-Life Reuse	Zero	100%	50%	Zero	74%
	End-Of-Life Biodegradable	Zero	Zero	Zero	90%	5%
	Water consumption	Zero	0.18m^3/m^2	0.69m^3/m^2	Zero	0.87m^3/m^2
Quality	Hazardous products	Zero	Zero	Zero	20%	1%
Energy flow	Embodied energy	0.7kWh/m^2	34.8kWh/m^2	56.81kWh/m^2	12.2kWh/m^2	104kWh/m^2
	Renewable energy	Zero	Zero	Zero	Zero	Zero
Emissions	Embodied carbon	1.7kgCO_2/m^2	3.4kgCO_2/m	11.2kgCO_2/m^2	3kgCO_2/m^2	19.4kgCO_2/m^2
	Liquid waste	Zero	Zero	Zero	Zero	Zero
	Solid waste	0.006kg/m^2	Zero	Zero	0.4kg/m^2	0.406kg/m^2

Table 9. The environmental impacts of proposed façade system.

The pre-rationalized model of the innovative proposed façade, with its focus from the very beginning on a ‘design for constructability approach’ allowed the maximum use of COVID-19 waste by 74%. Interestingly enough, the team has been able to bring the level of waste down to 3% to 5% on this project. The sharing of design principles through the MIVES played a large role in this achievement.

B.3 IMPACTE ECONÒMIC: VIABILITAT COMERCIAL (COSTOS / BENEFICIS) MERCAT POTENCIAL I VIABILITAT

La viabilitat de la solució presentada no només ha de ser viable des d'un punt de vista tècnic i de circularitat, sinó també des d'un punt de vista econòmic. En aquest apartat heu de calcular i justificar degudament quin és el cost de producció del vostre producte i/o prestació del servei tenint en compte els costos d'escala ja que no té el mateix cost produir 100 unitats que 10.000 unitats. En base aquest cost base, cal definir un preu de venda justificable des d'una perspectiva comercial i tenint en compte el tipus mercat al qual us adreceu i al perfil d'usuaris que creieu que adoptaran la vostra solució.

Informació de suport:

- *En la següent guia podreu veure els principals elements a tenir en compte per calcular el cost de producció i un preu de venda : link.*

The design and production of the SAMO developer’s façade, involved the creation of a large-scale solution that demanded careful design, engineering and optimisation in order to control costs. Any benefits, advantages or other justification, for every single element, was heavily challenged, based upon their associated a) fabrication and assembling cost, b) annual maintenance cost, and c) dismantling cost. The following section details these values in euros/m^2 for the proposed façade.

a) **Fabrication and assembling cost**: include the costs of design, fabrication, transportation and installations, which is a significant while inevitable indicator. Table 10 presenting the global fabrication and assembling cost of the developed concept. As shown the total fabrication cost of such an adaptive façade is very low comparing the other technologies due to the substituted waste materials as structure and filling components. This process of reducing the fabrication cost can be applied in all construction or rehabilitation process by good understanding of waste features.

Component	Material	Value	Quantity	Price	References
Face mask	PP	Zero	30 unit/m^2	Zero	-
Sanitizer bottle	PET	Zero	60 unit/m^2	Zero	-
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	Fabricate: 5,08 €/kg Include transport and labor	2.48 kg/m^2	12,59 €/m^2	[21]
Cover	TiO_2	1400-1600 €/t.	0.4 kg/m^2	6,1 €/m^2	
Multi-chip led	PCB Silicon	120 €/50m	8m/m^2	19 €/m^2	[33]
Total fabrication and assembling cost per each square meter				**37,69 €/m^2**	

Table 10. The partial and complete fabrication and assembling cost of the developed concept.

b) **Annual maintenance cost:** The term maintenance cost refers to any cost incurred to keep proposed façade in good functioning condition. These costs may be spent for the general maintenance of items like cleaning, repairing, replacing or technical revision. The maintenance process of adaptive façades, required highly professionals and long list of maintenance problems which can be solved by simplifying them and using low-cost materials. Moreover, application of TiO_2 totally eliminates the required cleaning cost for the proposed modules. Its super-hydrophilicity helps the surface dry faster, and prevent the undesirable water streaking or spotting on the surface. Following Table 11 presents in detail the maintenance cost of different IF alternatives in literature.

Component	Material	Maintenance	Quantity	Price

Face mask	PP	Renew once per year	30 unit/m²	Zero
Sanitizer bottle	PET	Zero	60 unit/m²	Zero
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	Zero	2.48 kg/m²	Zero
Cover	TiO_2	Renew after 3 years	0.4 kg/m²	3 €/m²/a
Multi-chip led	PCB Silicon	Zero	8m/m²	Zero
Annual maintenance cost of 1 square meter				**3 €/m²/a**

Table 11. Annual maintenance cost of the proposed concept.

c) **Dismantling cost:** Existing façade systems going to be restructured or demolished after their end-of-life phase. Such reconstruction interventions cause high bills, resource consumption and waste generation. This section deals with deconstructing and dismantling costs of proposed façade so as to recover as many parts as possible without leaving any debris on site. Table 12 showing the dismantling cost of the IFs and the main recovery potentials of their parts.

Component	Material	Labor	Quantity	Price	References
Face mask	PP	Zero	30 unit/m²	Zero	-
Sanitizer bottle	PET	Zero	60 unit/m²	Zero	-
Strut-bracket 70x5cm	1.4462 Duplex Stainless steel	0.36€/kg	2.48 kg/m²	0,9€/m²	[32]
Cover	TiO_2	Zero	0.4 kg/m²	Zero	-
Multi-chip led	PCB Silicon	Zero	8m/m²	Zero	-
Dismantling cost of 1 square meter				**1€/m²**	

Table 12. Dismantling cost of the proposed concept in end-of-life phase.

C | CONCLUSION	PARTIAL SUSTAINABILITY GLOBAL SUSTAINABILITY SENSITIVITY ANALYSIS

This research proposal has applied a recently developed MIVES assessment model able to quantify the sustainability of intelligent facades for the first time with a sensitivity analysis. This assessment model exclusively incorporates main indicators, from energy efficiency to social values. The application of this new model has proposed a new façade technology with the highest sustainability and partial satisfaction indexes as shown in Table 13. The developed proposal is a combination of assessed technologies, which provided a wide range of rehabilitation possibilities. This new proposal has been developed due to its low total production cost, while it will provide maximum energy efficiency, comfort and ease in assembling. However, it achieved low flexibility level due to required operator to move the tiles which can be optimized in future researches by application of linear actuators.

Indicator		Value	Indicator		Value
I1	Fabrication & assembling cost	37,69€/m²	**I8**	Recyclability	97%
I2	Maintenance cost	3€/m²/a	**I9**	Reusability	89%
I3	Dismantling cost	1€/m²/a	**I10**	Fabrication easiness	9/10
I4	Embodied energy	104.41 kWh/m²	**I11**	Flexibility	6/10
I5	Embodied carbon	19.46 $kgCO_2/m^2$	**I12**	Ventilation performance	5/10
I6	Energy saving	35%	**I13**	Lighting performance	7/10
I7	Energy conversion efficiency	-1.2%	**I14**	Reusability	8/10

Table 13. Main architectural features of proposed façade based on developed requirements tree.

The global sustainability index GS_k along with the partial satisfaction indexes for the proposed façade are presented in Table 14. As expected, the economic index for the proposed façade shifted considerably and stayed at the highest level. Mostly that is due to required production materials, which also has environmental factors.

Alternative	SI_{R1k}	SI_{R2k}	SI_{R3k}	GS_k
Proposed façade technology	1.00	0.88	0.69	0.83

Table 14. Resulting sustainability indexes for proposed alternative.

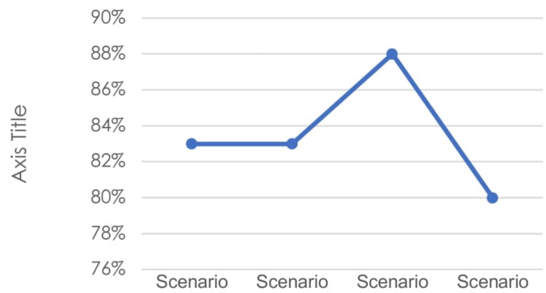
Legend: Sustainability Index for economic requirements (SI_{R1K}), Sustainability Index for environmental requirements (SI_{R2K}), Sustainability Index for social requirements (SI_{R3K}), Global Sustainability (GS_k).

The last step aims to analyze the sensitivity of the results. In this sense, the new facade system has been assessed through changing the assigned weights for requirements in four different scenarios. Table 15 illustrates the input scenarios. Scenario E1 corresponds to the economic, environmental and social weights originally proposed by the experts in previously developed MIVES tool. Alternatively, scenario E2 considers a balanced distribution of weights, in which the requirements have the same weight. In scenario E3, the final decision has been obtained with the greater weight placed on the economic requirement and finally, in scenario E4, the environmental requirement was assigned a greater weight. Finally, the robustness of this study is achieved when each requirement for each scenario for proposed façade does not have a variation more than ±10% from research project scenarios.

Sustainability requirement	Panelist scenario (E1)	Neutral scenario (E2)	Economically biased scenario (E3)	Environmentally biased scenario (E4)
Economic	34%	33.33%	50%	30%
Environmental	36%	33.33%	30%	50%
Social	30%	33.33%	20%	20%

Table 15. Variable scenarios used for sensitivity analyses.

The sensitivity analyses in three different scenarios and the proposed weights from the experts in MIVES provided more evidence for these results. In order to study the influence of MIVES on the ranking of the proposed façade, this study has compared through different weight assignments for each requirement.



	Scenario MIVES	Scenario E1	Scenario E2	Scenario E3	Variation E1 to E2	Variation E1 to E3	Variation E1 to E4
Proposal	83%	83%	88%	80%	0%	5%	-3%

Table 16. Sensitivity analysis and variations of each scenario.

As presented in Table 16, in all scenarios, the new proposed façade technology has performed great as anticipated and has placed in highest sustainability satisfaction. The variations are not significant and confirm the robustness for the approach used in this research project.

To sum up, this new proposal presents a new low-cost façade system which will be able to provide better comfort to our buildings' inhabitants and less emissions and energy consumption by rehabilitating their façades while reusing the sanitary waste from COVID-19 pandemic. This reuse implies recollection in health and educational centers that provides awareness for future generations.

In doing so, this proposal starts a new movement towards new circular façades for the future of our architecture in a better Society.

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ANNEXES

Annex A. The abbreviations used in the text.

Abbreviations	Relevant values
PET	Polyethylene Terephthalate
PP	Polypropylene
TTI	Time to Ignition
VAWT	Vertical Axis Wind Turbine
LCC	Life Cycle Assessment
LCA	Life Cost Assessment
MCDM	Multi-Criteria Decision Making
LED	Light Emitting Diodes
TiO_2	Titanium Dioxide
WWR	Window-to-Wall Ratio
MSW	Municipal Solid Waste
cDA	Continuous Daylight Autonomy
sDA	Spatial Daylight Autonomy

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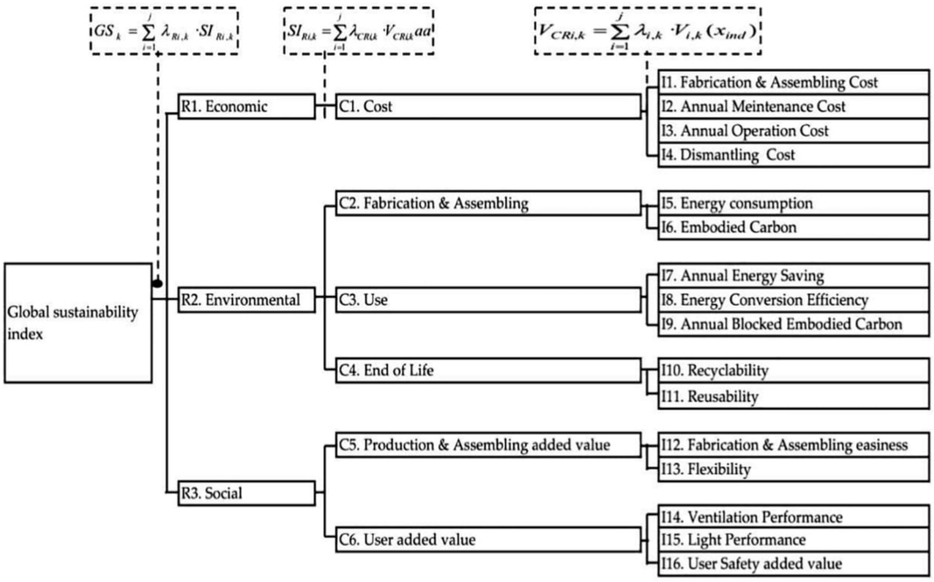
Annex B. The designed poster for collection of waste materials which has been shared in social medias.

Annex C. Requirements tree of the previously developed MIVES assessment tool.



Appendix G.

Certification of the participating in the the UPC Recircula challenge 2021.

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RECIRCULA CHALLENGE

Edición 2021

Este diploma certifica que:

SAEID HABIBI

ha participado en el Recircula Challenge.

En nombre de la Universitat Politècnica de Catalunya queremos agradecerte el esfuerzo que has realizado y te animamos a seguir impulsando nuevas maneras colaborativas, diferentes y divertidas para co-crear soluciones a retos reales y urgentes de la economía circular.

Barcelona, mayo de 2021

Hub Recircula UPC AMB

AMB Àrea Metropolitana de Barcelona

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