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MÉTODOS DE EVALUACIÓN DE LA EDIFICACIÓN SOSTENIBLE: ADAPTACIÓN AL CAMBIO CLIMÁTICO Y ESTRATEGIAS DE IMPLANTACIÓN

SUSTAINABLE BUILDING ASSESSMENT METHODS: ADAPTATION TO CLIMATE CHANGE AND IMPLEMENTATION STRATEGIES

Tesis Doctoral

Para la obtención del

Grado de doctor por la Universidad de Granada

Carmen Díaz López

Directores:

Montserrat Zamorano Toro, Manuel Carpio Martínez

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C. Díaz-López, M. Carpio, M. Martín-Morales, M. Zamorano, 2018. Catálogo de metodologías para la evaluación de edificación sostenible. Catálogo de metodologías para la evaluación de edificación sostenible. IX International Green Cities Congress. (Málaga, Spain) ISBN 978-84-09-01166-7

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LIBROS

C. Díaz López; J. J. de la Torre-Bayo; M. Zamorano; J. A. Holgado-Terriza; J. M. López-Torralba; J. Jódar; M. L Rodríguez-González; K. Verichev. Guía de edificación sostenible adaptada al cambio climático. pp. 1 - 162. Granada, Andalucía (Spain): 02/09/2019. ISBN: 978-84-09-14482-2. Depósito legal: GR 1001-2019

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AdapteCCa	Climate Change Adaptation Platform
AHP	Analytical Hierarchy Process
AR5	5th assessment report
C	Cooling
CDD	cooling degree–days
CSI	climatic severity index
CTE	Technical Building Code (Código Técnico de la Edificación in spanish)
CV	Pearson's Coefficient of Variation
CZ	climate zones
DB-HE	Basic Document on Energy Saving of the Technical Building Code
ED	Energy Demand
EU	European Commission
GBC	Green Building Council
GDP	Gross Domestic Product
GHG	anthropogenic greenhouse gas
GlobalABC	Global Alliance for Buildings and Construction
H	Heating
HDD	heating degree–days
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
KRNW	Knowledge Resource Nomination Worksheet
LCA	Life Cycle Assessment
NGO	non-governmental organisation
nZEB	net Zero Energy Building
RCP	Representative Concentration Pathway
RF	radiative forcing
RFtot	total Radiative Forcing
SBAM	sustainable building assessment method
SciMAT	Science Mapping Analysis Software Tool
SCS	climatic severity summer
SD	standard deviation
SDG	Sustainable Development Goal
SLR	systematic literature review
UN	United Nations
UNEP	United Nations Environment Programme
VoC	coefficient of variation
WHO	World Health Organization
WoS	Web of Science
WSC	climatic severity winter

RESUMEN

Desde la llegada del primer método de evaluación de la sostenibilidad en la edificación (MEES), *Transient System Simulation Tool* (TRNSYS), se han desarrollado una gran cantidad de instrumentos muy diferentes para evaluar la sostenibilidad de diferentes tipos de edificios. No obstante, la implementación de estos instrumentos se ve obstaculizada por desafíos importantes. Por un lado, la complejidad de la evaluación y la ausencia de un marco común de criterios entre los diferentes países genera incertidumbre en la comparación de edificios sostenibles entre sí. Por otro, las preocupaciones sobre los altos costos de capital inicial de la edificación sostenible a largo plazo crean un dilema para las partes interesadas, además de la falta de instrumentos fiscales, financieros y gubernamentales para implantar criterios de sostenibilidad en la industria. Asimismo, debido a los cambios demostrados sobre el clima, resulta imprescindible que estos métodos contemplen las consecuencias a lo largo de la vida útil del edificio.

Si bien existen estudios desarrollados sobre los MEESs, aún no se han estudiado en profundidad la amplia gama de factores que influyen desde el punto de vista de la adaptación al cambio climático, o las estrategias de implantación, ni las consecuencias que tendría sobre el incremento del desarrollo de edificación sostenible. En consecuencia, esta investigación ha tenido como objetivo principal alcanzar un conocimiento en profundidad sobre los MEESs existentes y su capacidad para adaptarse al cambio climático, así como el desarrollo de estrategias para facilitar su implantación. Para alcanzarlo se ha analizado la evolución científica de la

edificación sostenible y de los MEESs; se ha estudiado y comparado los métodos existentes; y, finalmente se han identificado y sentado las bases para el desarrollo de estrategias dirigidas a facilitar e impulsar la implantación de estos.

Los resultados obtenidos muestran un campo científico en constante evolución, desde su enfoque inicial en los impactos ambientales hasta la inclusión paulatina de los aspectos sociales y económicos de la sostenibilidad. Además, ponen de manifiesto que cada uno de los MEESs por separado no evalúa todas las variables del edificio. Estos resultados han sido contundentes en cuanto a la valoración positiva de Level(s) por parte de los expertos, un nuevo marco establecido por la Comisión Europea en materia de edificación adaptada al paradigma de la Economía Circular; de hecho, se ha identificado como el método hoy en día más completo, destacando factores como su respuesta a la necesidad de adaptar los edificios al cambio climático, su lenguaje de referencia estándar y su uso en múltiples situaciones. Por este motivo, se han establecido las estrategias clave a llevar a cabo para la implementación de Level(s), entre las que se destacan la identificación del efecto del cambio climático sobre la edificación y la identificación de incentivos para el fomento de la edificación sostenible y su evaluación. Además, se destaca que la actual falta de regulaciones sobre la adaptación de los edificios al cambio climático da lugar a un *stock* de construcción obsoleto, que es incapaz de hacer frente al dinamismo climático que ya se está produciendo.

Se concluye que los resultados obtenidos en este trabajo son una contribución valiosa para todas las partes interesadas, ya que brinda a los expertos del campo de la edificación una visión integral del *status quo* y predice las direcciones dinámicas de la investigación futura.

ABSTRACT

Since the advent of the first sustainable building assessment method (SBAM), Transient System Simulation Tool (TRYNNS), many very different methods have been developed to assess the sustainability of buildings. However, significant challenges have hampered the implementation of these instruments. On the one hand, the complexity of the assessment and the absence of a common framework of criteria across countries creates uncertainty in comparing sustainable buildings with each other. On the other hand, concerns regarding the high upfront capital costs of sustainable building in the long term and the lack of fiscal, financial and governmental instruments for implementing sustainability criteria create a dilemma for stakeholders. Furthermore, due to the demonstrated changes in climate, these methods must consider the consequences over the lifetime of the building.

Although SBAMs have been widely studied, the wide range of factors influencing climate change adaptation, implementation strategies and the consequences for increased sustainable building development have not yet been studied in depth. Consequently, the main objective of this research is to gain an in-depth understanding of existing SBAMs and their capacity to adapt to climate change and develop strategies to facilitate their implementation. The scientific evolution of sustainable building and SBAMs are analysed, existing methods are studied and compared, and the bases for the development of strategies aimed at facilitating and promoting their implementation are identified and laid.

The results obtained show a scientific field in constant evolution, from its initial focus on environmental impacts to the gradual inclusion of social and economic aspects of sustainability. Furthermore, they show that each of the individual methods does not assess all building variables. These results are conclusive in the experts' positive assessment of Level(s), a new framework established by the European Commission on building adapted to the circular economic paradigm. Level(s) are identified as the complete method to date, highlighting factors such as its response to the need to adapt buildings to climate change, its standard reference language and its use in multiple situations. For this reason, key strategies for the implementation of Level(s) are established, including identifying the effect of climate change on buildings and identifying incentives for the promotion of sustainable building and their evaluation. Furthermore, it is highlighted that the current lack of regulations on the adaptation of buildings to climate change results in an obsolete building stock, which is unable to cope with the climate dynamism that is already occurring.

It is concluded that the results obtained in this work are a valuable contribution to all stakeholders, as they provide experts in the building field with a comprehensive view of the status quo and predict dynamic directions for future research.

INTRODUCCIÓN, MOTIVACIÓN Y OBJETIVOS

1. Introducción

Los edificios y su entorno construido constituyen un sistema organizativo complejo que contribuye al desarrollo social, económico y ambiental de cualquier país (Alawneh et al., 2019), además de albergar el contexto físico para las interacciones sociales y el desarrollo económico a nivel micro. No obstante, y a pesar de las múltiples oportunidades y beneficios que brindan, este sector industrial es responsable de la aceleración del cambio climático, del agotamiento de los recursos naturales, de la generación de residuos y la desigualdad social (Xu et al., 2012). Así, cada fase del ciclo vida de esta actividad, que incluye su construcción, uso, demolición y eliminación, crea una carga significativa que varía considerablemente según el tipo y la ubicación de la construcción (Darko et al., 2017; Macías & Navarro, 2010). De hecho, según datos del Programa de las Naciones Unidas para el Medio Ambiente, a nivel mundial este sector representa el 35% del consumo energético anual y el 38% de las emisiones de CO_2 (GlobalABC/IEA/UNEP, 2020), habiendo duplicado su consumo entre 1973-2012 y, por consiguiente, aumentado las emisiones antropogénicas de gases de efecto invernadero (GEI) (IPCC, 2014). A este impacto se suma el consumo del 30% de las materias primas y el 25% del agua global (Giannetti et al., 2018) y 17% del agua dulce (Dixit et al., 2013), además de ocupar el 12% de la superficie del suelo (Dong & Ng, 2015), así como generar el 25% de los residuos sólidos de los países desarrollados y el 40% en los que están en vías de desarrollo (Yılmaz & Bakış, 2015).

A todos los problemas indicados, se unen los relacionados con la salud y el bienestar. Según datos de la Organización Mundial de la Salud (OMS), desde el 2016 el 90% de los habitantes de las ciudades respira aire que no cumple las normas de seguridad establecidas, lo que provocó un total de 4.2 millones de muertes debido a la contaminación atmosférica (Organization, 2016). Asimismo, más de un 13% de personas en el mundo viven sin electricidad, y otros 3000 millones utilizan combustibles contaminantes como leña u otra biomasa para cocinar o acondicionar térmicamente sus viviendas. De esta forma el acceso a los sistemas térmicos activos se considera en muchas regiones un lujo, debido a su alto costo; de hecho sólo el 8% de los 2800 millones de personas que viven en las zonas más calurosas disponen de sistemas de enfriamiento (Bhatia & Angelou, 2015). Estos altos índices de vulnerabilidad se acentúan entre la población de riesgo con bajos recursos que viven en edificios de baja calidad, ubicados en lugares peligrosos o sin servicios adecuados que cumplan unas garantías mínimas de calidad, provocando diversas enfermedades (Ahmad & Puppim De Oliveira, 2015).

Todos estos impactos negativos, que se viene dando ya desde la Segunda Guerra Mundial, está degenerando en la creación de mayores potenciales de toxicidad ambiental y en desigualdades sociales y regionales. Además, según el quinto informe de evaluación del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC, 2014), se predice un aumento en la temperatura promedio global para el año 2100 en el rango de 1.4 a 5.8 °C. Se estima que de seguir con el actual patrón, el consumo energético de los edificios podría duplicarse o incluso triplicarse para el año 2050 (IPCC, 2014). Igualmente, debido al aumento de la población mundial, la urbanización descontrolada y el reemplazo de edificios existentes, en los próximos 40 años se necesitará colonizar más terreno natural que en los últimos 4000 (Eberhardt et al., 2019).

A todo lo indicado hay que sumar que los edificios corren grandes riesgos de sufrir colapso inducido por desastres naturales y por los impactos previstos del cambio climático (GlobalABC/IEA/UNEP, 2020). Esto puede llegar a provocar la posible pérdida de activos y, lo que es más importante, de vidas humanas (Pan et al., 2014). Por ello, y con el fin de encaminar al sector hacia la neutralidad de emisiones para 2050, la Agencia Internacional de Energía (AIE) estima que para 2030 las emisiones directas de CO_2 de los edificios deben disminuir un 50%, y un 60% en el caso de las emisiones indirectas. Esto equivale a una caída de las emisiones de alrededor de 6% anual hasta 2030 (GlobalABC/IEA/UNEP, 2020). Según Inger Andersen, directora ejecutiva del Programa de las Naciones Unidas para el Medio Ambiente (PNUMA), “transitar hacia un sector construcción bajo en carbono ralentizará el cambio climático y generará importantes beneficios para la recuperación económica, por lo que debería ser una prioridad clara para todos los gobiernos".

1.1. Evolución de la edificación sostenible

Como respuesta a la problemática descrita, hace más de medio siglo comenzó a desarrollarse el concepto de edificación sostenible. Este término abarca los edificios, el entorno construido y la manera en la que se integran para configurar las ciudades. Además, dado el impacto de la globalización en el sector resulta evidente que los puntos de inflexión en la evolución de la idea de edificación sostenible están intrínsecamente ligados a los cambios de mentalidad de las industrias satélites. Por todo ello, el nuevo paradigma de construcción ha ido evolucionando en paralelo al desarrollo socioeconómico mundial.

La definición temprana de edificio sostenible comienza a vislumbrarse a principio de los años setenta debido a las consecuencias ambientales y económicas de la llamada Sociedad Industrial. La industria empieza a poner énfasis en la conservación de la energía y la eficiencia energética, y comienzan las críticas hacia la denominada "economía lineal" y la sociedad de "usar y tirar". En el primer informe del Club de Roma, publicado en 1972 (Robinson, 1973), conocido como "Los límites del crecimiento", se afirmó que "si la industrialización, la contaminación ambiental, la producción de alimentos y el agotamiento de los recursos mantienen las tendencias actuales de crecimiento de la población mundial, este planeta alcanzará los límites de su crecimiento en el curso de los próximos cien años. El resultado más probable sería un súbito e incontrolable descenso tanto de la población como de la capacidad industrial”. No es hasta la década de los ochenta cuando surge el concepto de desarrollo sostenible. En 1987, la Comisión Bruntland (Asamblea General de las Naciones Unidas) definió por primera vez el concepto de desarrollo sostenible como, "aquel que satisface las necesidades del presente sin comprometer la capacidad de las generaciones futuras para satisfacer sus propias necesidades" (Brundtland et al., 1987). Este desarrollo puede obtenerse abordando simultáneamente los problemas económicos, ambientales y sociales, es decir, los llamados "tres pilares" de la sostenibilidad (Boutros-Ghali, 1995).

En este contexto, la edificación sostenible se promulgó y promovió como paradigma rector del desarrollo sostenible en el sector de la construcción (Dobson et al., 2013). Según lo expresado en el documento *Communication from the commission to the council, the European parliament, the European economic and social committee and the committee of the regions - Towards a thematic strategy on the urban environment*, “La edificación sostenible es el proceso en que todos los actores implicados (propiedad, proyectistas, constructores, equipo facultativo, suministradores de materiales, administración, usuarios, entre otros) integran las consideraciones funcionales, económicas, ambientales y de calidad para producir y renovar los edificios y su entorno”.

Desde entonces, y a partir de la década de los 90, se han realizado esfuerzos notables alrededor de todo el mundo que han permitido identificar los temas fundamentales y cómo abordarlos. Especial mención merece la denominada Carta de Aalborg, resultado de la Conferencia Europea de Ciudades y Pueblos Sostenibles realizada en 1994 en Dinamarca (Levine, 1995). Este documento está inspirado en el plan de la Agenda 21 Local de la Cumbre de la Tierra de Río y fue desarrollado para contribuir al Programa de Acción Ambiental de la Unión Europea (UE), "Hacia la Sostenibilidad". En este marco las ciudades adquirieron el reto y compromiso de integrar los principios del desarrollo sostenible en sus políticas locales.

Otro hito fundamental fue el Protocolo de Kioto de 1997 (United Nations, 1998), en el que los países industrializados reunidos en la ciudad de Kioto, Japón, llegaron al compromiso de reducir las GEI. Este tratado supuso el primer reconocimiento de responsabilidad por parte de los gobiernos ante el cambio climático. El compromiso consistió en alcanzar una reducción de al menos un 5% en el promedio de emisiones GEI entre 2008 y 2012, tomando como referencia los niveles de 1990. Si bien este compromiso únicamente mitigaba los efectos nocivos del calentamiento global sin tener aun en cuenta la necesidad imperante de la adaptación de la edificación al dinamismo climático.

Pero no ha sido hasta la última década cuando el concepto de edificación sostenible ha alcanzado su mayor auge entre todas las partes interesadas. El 25 de septiembre de 2015 los 193 estados miembros de las Naciones Unidas (NU) aprobaron la Agenda 2030 sobre el Desarrollo Sostenible, una oportunidad para que los países y sus sociedades emprendan un nuevo camino con el que mejorar la vida de todos, sin dejar a nadie atrás. La Agenda cuenta con 17 Objetivos de Desarrollo Sostenible, cada uno de los cuales incluye un conjunto de metas destinadas a la eliminación de la pobreza hasta el combate al cambio climático, la educación, la igualdad de la mujer, la defensa del medio ambiente o el diseño de nuestras ciudades. Entre las metas recogidas en los ODS, y que deberían ser alcanzadas en el 2030 en materia de edificación se encuentran: la reducción sustancial del número de muertes y enfermedades producidas por mala praxis en la edificación; duplicar la tasa mundial de mejora de la eficiencia energética con respecto al año 2012; el aumento de la urbanización inclusiva y sostenible, la planificación y la gestión participativas; y la creación de ganancias netas de las actividades económicas mediante la reducción de la utilización de los recursos, la degradación y la contaminación. Todas ellas contribuirán a lograr una mejor calidad de vida, y constituirán el eje de los esfuerzos para hacer frente al cambio climático (UN General Assembly, 2015).

La implantación de las medidas indicadas está implicando una evolución del concepto de edificación sostenible hacia su adaptación al cambio climático. Esto es debido a que, si bien una edificación sostenible es clave para mitigar los efectos negativos del dinamismo climático, este sector debe prever con la misma eficacia los efectos adversos del mismo y tomar las medidas oportunas para evitar y minimizar los daños que puedan causar a medio y largo plazo. De este modo surge la necesidad de diseñar edificios resilientes capaces de utilizar y optimizar los recursos naturales para la mejora de las condiciones de habitabilidad, la capacidad y funcionalidad del edificio durante toda su vida útil. Un edificio resiliente es aquel capaz de cambiar su uso y reorganizar su espacio en situaciones de emergencia; además de soportar condiciones adversas y continuar operativo después de una catástrofe durante todo su ciclo de vida. Por ello, la resiliencia de la edificación y su entorno construido frente a los impactos del cambio climático y las alteraciones asociadas es un tema importante que ha recibido una atención cada vez mayor en los últimos años (McAllister & McAllister, 2013). Por ejemplo, el Pacto Verde Europeo identificó los edificios resistentes al clima y con bajas emisiones de carbono como claves para lograr un continente resistente y neutral en carbono (European Commission, 2019). Una ciudad sostenible sin resiliencia perdería los beneficios obtenidos durante el desarrollo sostenible debido a la incapacidad de adaptarse a las amenazas (Bank, 2018).

1.2. Beneficios de la edificación sostenible

El actual concepto de edificación sostenible conlleva un enfoque sistemático que tiene en cuenta el clima, la sociedad y las materias primas locales (Carmen Díaz-López et al., 2021; He et al., 2021; Thomas & Praveen, 2020), además de incorporar tecnologías que reducen el uso de recursos, la huella ecológica (Collins et al., 2018) y los costos asociados durante el ciclo de vida (AbouHamad & Abu-Hamd, 2019). En consecuencia, los beneficios de un edificio sostenible se pueden agrupar en tres aspectos: ambiental, económico y social. Los beneficios ambientales circunscriben la conservación de los recursos naturales y una reducción de la huella ecológica (Bastianoni et al., 2006). Los económicos incluyen mayores rendimientos en la venta y el alquiler, mayores tasas de ocupación y productividad, y una reducción de los costos a largo plazo, de hecho, este sector proporciona del 5 al 10% del empleo y genera del 5 al 15% del Producto Interior Bruto (PIB) de cada país. Finalmente, los beneficios sociales determinan la ergonomía ambiental y el equilibrio para todas las partes interesadas (Balaban & Puppim de Oliveira, 2017; Dirisu et al., 2019). Además, el sector de la edificación contribuye a la creación de nuevos puestos de trabajo, impulsa el crecimiento económico y proporciona soluciones para los desafíos sociales, climáticos y energéticos. Se estima que la rehabilitación de edificios existentes más eficientes crearía entre 9 y 30 puestos de trabajo por cada millón de dólares invertidos en medidas de eficiencia energética en el sector de la construcción (Energy Agency, 2020).

A la luz de las ventajas de los edificios sostenibles, numerosos países de todo el mundo están llevando a cabo diferentes estrategias para su implantación, tanto en obra nueva como en la rehabilitación. Estos instrumentos están dando esperanzas al sector; de hecho, según datos del Informe sobre el estado global de los edificios y la construcción de 2020, de la Alianza Global para los Edificios y la Construcción (GlobalABC), en 2019, el gasto en edificios energéticamente eficientes aumentó por primera vez en tres años, y la eficiencia energética de los edificios en los mercados mundiales aumentó a 152.000 millones de dólares en 2019, un 3% más que el año anterior (United Nations Environment Programme, 2020).

En esta línea, en enero de 2021, la presidenta von der Leyen, en su discurso sobre el estado de la Unión de 2020 (European Commission, 2020), anunció la Nueva Bauhaus europea (President & Gabriel, 2021). Se trata de un proyecto medioambiental, económico y cultural, cuyo objetivo es combinar diseño, sostenibilidad, accesibilidad, asequibilidad e inversión para ayudar a conseguir el Pacto Verde Europeo, la nueva hoja de ruta destinada a dotar a la UE de una economía sostenible. Alcanzar el citado pacto exigirá de la transformación de los retos climáticos y medioambientales en oportunidades en todos los ámbitos políticos y lograr, así, una transición justa e integradora para todos. A través de la implicación de ciudadanos, expertos, empresas e instituciones, se pretende resaltar el valor de la simplicidad, la funcionalidad y la circularidad de los materiales sin comprometer la necesidad de comodidad y atractivo en nuestra vida diaria; brindando apoyo financiero a ideas y productos innovadores.

1.3. Evaluación de la edificación sostenible

Dentro del nuevo paradigma descrito surge la necesidad de evaluar el alcance de las medidas que se están adoptando en materia de edificación sostenible; es ahí dónde subyace el concepto de método de evaluación de la edificación sostenible (MEES). Desde la década de los 70, se dispone de más de 600 métodos que buscan sintetizar de forma cuantitativa y objetiva el comportamiento y rendimiento del edificio y sus impactos (López et al., 2019). Estos instrumentos están basados en un conjunto de criterios que proporcionan indicadores cuantitativos y cualitativos de desempeño ambiental, económicos, sociales y de usabilidad, actualizándose continuamente en paralelo al concepto de edificación sostenible. No son una simple herramienta de medición del edificio, sino una metodología de diseño, de apoyo a las partes interesadas y cuyo fin sería la materialización de la concepción holística de la tan ansiada sostenibilidad. Existe una amplia gama de estudios sobre los MEEs, centrados en discutir, comparar y debatir las características de un gran grupo de estos instrumentos. Sin embargo, no se ha estudiado en profundidad el amplio conjunto de factores internos y externos que influyen a la hora de implantar y desarrollar criterios de sostenibilidad, ni las consecuencias que tendrían sobre el incremento o no del uso de los MEESs.

Además, en los últimos años se está empezando a considerar la adaptación de la edificación al cambio climático dentro del paradigma de la economía circular, un modelo económico que se interrelaciona con la sostenibilidad, y cuyo objetivo es que el valor de los productos, los materiales y los recursos se mantenga en la economía durante el mayor tiempo posible, y que se reduzca al mínimo la generación de residuos (Akanbi et al., 2018). Esto permite evaluar el rendimiento del proceso de edificación desde etapas muy tempranas, lo que facilita una toma de decisiones correctas, no sólo en su construcción, sino a lo largo de toda la vida útil del edificio, repercutiendo en su consumo energético, calidad del aire interior, reciclado y reutilización de los materiales, así como, su resiliencia ante el dinamismo climático.

No obstante, la implementación generalizada de los MEESs se ve obstaculizada por desafíos importantes. Por un lado, la complejidad de la evaluación y certificación de la sostenibilidad del edificio, así como consecuencia la ausencia de un marco común de criterios entre los diferentes países y entre los aspectos que hacen que un edificio sea ciertamente sostenible, genera incertidumbre a la hora de poder comparar edificios sostenibles entre sí. Por otro, las preocupaciones sobre los altos costos de capital inicial, la financiación y la amortización de la edificación sostenible a largo plazo, crean un dilema para las partes interesadas (Salem et al., 2018). Además, la falta de instrumentos fiscales, financieros y gubernamentales para implantar criterios de sostenibilidad en la industria ha demostrado que sin incentivos resulta muy complicado el desarrollo de una edificación ciertamente sostenible. Asimismo, debido a los cambios demostrados sobre el clima, resulta imprescindible que estos métodos contemplen las consecuencias a lo largo de la vida útil del edificio, adoptando soluciones lo mitiguen, pero que también se adapten a los diferentes escenarios a lo largo del tiempo. El escaso conocimiento sobre la materia hace que este desafío sea uno de los grandes retos a los que hacer frente.

1.4. Motivación y objetivos

Por todo lo expuesto, los métodos edificación sostenible son herramientas claves para potenciar la edificación sostenible, y la adaptación de esta al cambio climático, desde el punto de vista ambiental, económico y social. Si bien existen estudios sobre los MEESs, aún no se han analizado en profundidad la amplia gama de factores internos y externos que influyen desde el punto de vista de la adaptación al cambio climático; tampoco las estrategias de implantación fiscales, administrativas, y financieras, ni las consecuencias que tendría sobre el incremento del desarrollo de edificación sostenible.

En consecuencia, esta investigación ha tenido como objetivo principal alcanzar un conocimiento en profundidad sobre los MEESs existentes y su capacidad para adaptarse al cambio climático, así como el desarrollo de estrategias para facilitar su implantación. Para alcanzar este objetivo principal se han definido los siguientes objetivos secundarios:

(i) Analizar la evolución científica de la edificación sostenible y de los MEESs.

(ii) Estudiar y comparar los MEESs existentes.

(iii) Identificar y sentar las bases para el desarrollo de estrategias dirigidas a facilitar e impulsar la implantación de MEESs.

INTRODUCTION, MOTIVATION AND OBJECTIVES

1. Introduction

Buildings and their built environment constitute a complex organisational system that contributes to the social, economic and environmental development of any country (Alawneh et al., 2019), and hosting the physical context for social interactions and economic development at the micro-level. However, despite the multiple opportunities and benefits they provide, this industrial sector is responsible for accelerating climate change, natural resource depletion, waste generation and social inequality (Xu et al., 2012). Thus, each phase of the life cycle of this activity, which includes its construction, use, demolition and disposal, creates a significant burden that varies considerably depending on the type and location of the construction (Darko et al., 2017; Macías & Navarro, 2010). In fact, according to data from the United Nations (UN) Environment Programme, globally, this sector accounts for 35% of annual energy consumption and 38% of CO_2 emissions

(GlobalABC/IEA/UNEP, 2020), having doubled its consumption between 1973–2012 and consequently increased anthropogenic greenhouse gas (GHG) emissions (IPCC, 2014). Adding to this impact is the consumption of 30% of raw materials, 25% of global water (Giannetti et al., 2018) and 17% of freshwater (Dixit et al., 2013), as well as occupying 12% of land area (Dong & Ng, 2015) and generating 25% of solid waste in developed countries and 40% in developing ones (Yılmaz & Bakış, 2015).

In addition to all of the above problems, there are also problems related to health and well–being. According to data from the World Health Organization (WHO), since 2016, 90% of city dwellers breathe air that does not meet established safety standards, which has resulted in a total of 4.2 million deaths due to air pollution (Organization, 2016). Furthermore, more than 13% of the world's people live without electricity, and another 3 billion people use polluting fuels such as wood or other biomass for cooking or heating their homes. Thus, access to active thermal systems is considered a luxury in many regions due to their high cost; in fact, only 8% of the 2.8 billion people living in the hottest areas have cooling systems (Bhatia & Angelou, 2015). These high vulnerability rates are accentuated among at-risk populations with low resources who live in low-quality buildings, located in dangerous places or without adequate services that meet minimum quality guarantees, causing various diseases (Ahmad & Puppim De Oliveira, 2015).

All these negative impacts, which have been occurring since the Second World War, have led to the creation of greater potential environmental toxicity and social and regional inequalities. Furthermore, according to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014), the global average temperature is predicted to increase by 2100 in the range of 1.4 to 5.8 °C. It is estimated that if the current pattern continues, the energy consumption of buildings could double or even triple by 2050 (IPCC, 2014). Due to global population growth, uncontrolled urbanisation and the replacement of existing buildings, more natural land will need to be colonised in the next 40 years than in the last 4000 years (Eberhardt et al., 2019).

In addition, buildings are at high risk of collapse induced by natural disasters and the expected impacts of climate change. It can lead to the potential loss of assets and, more importantly, human lives (Pan et al., 2014). Therefore, to put the sector on track towards emission neutrality by 2050, the International Energy Agency estimates that by 2030, direct CO_2 emissions from buildings should be reduced by 50% and indirect emissions by 60%, equating to a fall in emissions of ~6% per year until 2030 (GlobalABC/IEA/UNEP, 2020). According to Inger Andersen, executive director of the United Nations Environment Programme (UNEP), "moving towards a low-carbon building sector will slow climate change and generate significant benefits for economic recovery and should be a clear priority for all governments".

1.1. Evolution of sustainable building

In response to the problems described above, the concept of sustainable building first began to develop more than half a century ago. This term encompasses buildings, the built environment and how they are integrated to shape cities. Moreover, given the impact of globalisation on the sector, it is clear that the turning points in the evolution of sustainable building are intrinsically linked to changes in the mindset of the satellite industries. As a result, this new building paradigm has evolved in parallel with global socio-economic development.

The early definition of sustainable building began to emerge in the early 1970s due to the environmental and economic consequences of the so—called industrial society. At this time, industry began to emphasise energy conservation and efficiency, and criticism of the so-called "linear economy" and the "throwaway" society begum. In the first report of the Club of Rome, published in 1972 (Robinson, 1973), known as "The Limits to Growth", it was stated that "if industrialisation, environmental pollution, food production and resource depletion maintain present trends of world population growth, this planet will reach the limits of its growth within the next hundred years. The most likely outcome would be a sudden and uncontrollable decline in both population and industrial capacity". Nevertheless, it was not until the 1980s that the concept of sustainable development emerged. In 1987, the Bruntland Commission (United Nations General Assembly) first defined the concept of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987). Such development can be achieved by simultaneously addressing economic, environmental and social problems, i.e., the so-called "three pillars" of sustainability (Boutros-Ghali, 1995).

In this context, sustainable building was promulgated and promoted as a guiding paradigm for sustainable development in the building sector (Dobson et al., 2013). As expressed in a communication from the commission to the council, the European Parliament, the European economic and social committee and the committee of the regions –Towards a thematic strategy on the urban environment: "Sustainable building is the process in which all actors involved (owners, planners, constructors, specifiers, material suppliers, administration and users) integrate functional, economic, environmental and quality considerations to produce and renovate buildings and their environment". Since then, and from the 1990s onwards, remarkable efforts have been made worldwide to identify the key issues and how to address them. Special mention should be made of the so-called Aalborg Charter, the result of the European Conference on Sustainable Cities and Towns held in 1994 in Denmark (Levine, 1995). This document is inspired by the Local Agenda 21 plan of the Rio Earth Summit and was developed to contribute to the European Union's Environmental Action Programme, "Towards Sustainability". In this framework, cities were challenged and committed to integrating sustainable development principles into their local policies.

Another key milestone was the Kyoto Protocol of 1997 (United Nations, 1998), in which industrialised countries met in the city of Kyoto and were committed to reducing GHG emissions. This treaty was the first recognition of government responsibility for climate change. The commitment was to achieve at least a 5% reduction in average GHG emissions between 2008 and 2012, based on 1990 levels. However, this commitment only mitigated the harmful effects of global warming without considering the imperative need to adapt buildings to climate change.

Furthermore, it is only in the last decade that the concept of sustainable building has reached its peak among all stakeholders. On 25 September 2015, the 193 members states of the UN adopted the 2030 Agenda for Sustainable Development, an opportunity for countries and their societies to embark on a new path to improve the lives of all, leaving no one behind. The Agenda has 17 Sustainable Development Goals (SDGs), each of which includes a set of targets aimed at eliminating poverty, combating climate change, education, women's equality, environmental protection and our cities' design. Among the targets included in the SDGs, and which should be achieved by 2030 in terms of buildings, are a substantial reduction in the number of deaths and illnesses caused by building malpractice; doubling the global rate of improvement in energy efficiency; increasing inclusive and sustainable urbanisation, participatory planning and management; and creating net gains from economic activities by reducing resource use, degradation and pollution. All of these will contribute to achieving a better quality of life and will be at the heart of efforts to address climate change (UN General Assembly, 2015).

The implementation of the above measures implies an evolution of the concept of sustainable building towards adaptation to climate change. While sustainable building is key to mitigating the adverse effects of climate change, this sector must also effectively anticipate the adverse effects of climate change and take appropriate measures to avoid and minimise the damage it can cause in the medium and long term. This gives rise to the need to design resilient buildings capable of optimising natural resources to improve the habitability conditions, capacity and functionality of the building throughout its useful life. A resilient building can change its use and reorganise its space in emergencies; it can withstand adverse conditions and remain operational after a disaster throughout its life cycle. Therefore, the resilience of buildings and their built environment to the impacts of climate change and associated disturbances is an important issue that has received increasing attention in recent years (McAllister & McAllister, 2013). For example, the European Green Pact identified climate–resilient and low–carbon buildings as key to achieving a resilient and carbon-neutral continent (European Commission, 2019). A sustainable city without resilience would lose the gains made during sustainable development due to the inability to adapt to hazards (Bank, 2018).

1.2. Benefits of sustainable building

The current concept of sustainable building entails a systematic approach that takes into account climate, society and local raw (Díaz-López et al., 2021; He et al., 2021; Thomas & Praveen, 2020), as well as incorporating technologies that reduce resource use, ecological footprint (Collins et al., 2018) and associated life–cycle costs (AbouHamad & Abu-Hamd, 2019). Consequently, the benefits of a sustainable building can be grouped into three aspects: environmental, economic and social. The environmental benefits circumscribe the conservation of natural resources and a reduced ecological footprint (Bastianoni et al., 2006). Economic benefits include higher returns on sales and rentals, higher occupancy rates and productivity, and a reduction in long-term costs. This sector provides 5–10%

of employment and generates 5–15% of each country's gross domestic product. Finally, social benefits determine environmental ergonomics and balance for all stakeholders (Balaban & Puppim de Oliveira, 2017; Dirisu et al., 2019). Furthermore, the building sector contributes to creating new jobs, drives economic growth and provides solutions to social, climate and energy challenges. It is estimated that retrofitting more efficient existing buildings would create between 9 and 30 jobs for every USD 1 million invested in energy efficiency measures in the building sector (Energy Agency, 2020).

In light of the benefits of sustainable buildings, many countries worldwide are pursuing different strategies for their implementation, both in new construction and retrofitting. These instruments are giving hope to the sector; according to data from the Global Alliance for Buildings and Construction's (GlobalABC) 2020 Global State of Buildings and Construction Report, in 2019, spending on energy-efficient buildings increased for the first time in three years, and the energy efficiency of buildings in global markets increased to USD 152 billion in 2019, up 3% from the previous year (United Nations Environment Programme, 2020).

In this vein, in January 2021, President von der Leyen, in her 2020 State of the Union Address (European Commission, 2020), announced the New European Bauhaus (President & Gabriel, 2021). This is an environmental, economic and cultural project, which aims to combine design, sustainability, accessibility, affordability and investment with helping achieve the European Green Pact, the new roadmap for a sustainable European Union economy. Achieving the Pact will require transforming climate and environmental challenges into opportunities across all policy areas to achieve a just and inclusive transition for all. Through the involvement of citizens, experts, companies and institutions, it aims to highlight the value of simplicity, functionality and circularity of materials without compromising the need for comfort and attractiveness in our daily lives, providing financial support for innovative ideas and products.

1.3. Sustainable building assessment

Within the new paradigm described above, there is a need to assess the extent to which sustainable building measures are being taken; hence, the concept of the sustainable building assessment method (SBAM). Since the 1970s, more than 600 methods have been available that seek to quantitatively and objectively synthesise building behaviour, performance and impacts (Cole, 1998; Díaz López et al., 2019; Haapio & Viitaniemi, 2008). These instruments are based on criteria that provide quantitative and qualitative indicators of environmental, economic, social and usability performance and are continuously updated in parallel to the concept of sustainable building. They are not a simple building measurement tool but a design methodology, supporting stakeholders and aiming to realise the holistic conception of the longed-for sustainability. There is a wide range of studies on SBAMs, focusing on discussing, comparing and debating the characteristics of a large group of SBAMs. However, the wide range of internal and external factors that influence the implementation and development of sustainability criteria and their consequences on whether or not the use of SBAMs increases has not been studied in depth.

Furthermore, in recent years, building adaptation to climate change is beginning to be considered within the circular economy paradigm. This economic model is interlinked with sustainability, which aims to keep the value of products, materials and resources in the economy for as long as possible and minimise waste generation (Akanbi et al., 2018). This allows the performance of the building process to be assessed at a very early stage, facilitating sound decision making, not only at the construction stage but throughout the life of the building, impacting its energy consumption, indoor air quality, recyclability and reusability of materials, as well as its resilience to climate dynamism.

However, the widespread implementation of SBAMs is hampered by significant challenges. On the one hand, the complexity of assessing and certifying building sustainability and, consequently, the lack of a common framework of criteria between countries and the aspects that make a building genuinely sustainable creates uncertainty when comparing sustainable buildings. On the other hand, concerns regarding high upfront capital costs, financing and the long-term payback of sustainable building create a dilemma for stakeholders (Salem et al., 2018). The lack of fiscal, financial and governmental instruments for implementing sustainability criteria in the industry has shown that it is complicated to develop a truly sustainable building without incentives. Furthermore, due to the demonstrated changes in climate, these methods must consider the consequences throughout the building's life, adopting solutions that mitigate it and adapt to different scenarios over time. The lack of knowledge on the subject makes this one of the most significant challenges.

1.4. Motivation and objectives

Given the above, SBAMs are vital tools to promote sustainable building and adaptation to climate change from the environmental, economic and social points of view. Although studies on SBAMs exist, the wide range of internal and external factors influencing climate change adaptation, the fiscal, administrative and financial implementation strategies, and the consequences for increased sustainable building development have not yet been analysed in depth.

Consequently, the main objective of this research was to gain an in-depth understanding of the existing methods for assessing sustainable building and its capacity to adapt to climate change and develop strategies to facilitate its implementation. In order to achieve this objective, the following secondary objectives have been defined:

(i) To analyse the scientific evolution of sustainable building and SBAMs.

(ii) To study and compare existing SBAMs.

(iii) To identify and lay the foundations for the development of strategies aimed at facilitating and promoting the implementation of SBAMs.

PART I BACKGROUND

CHAPTER 1

Analysis of the scientific evolution of sustainable building and its evaluation methods[1]

[1] The results shown in this chapter were presented in: C. Díaz-López, M. Carpio, M. Martín-Morales, M. Zamorano. Analysis of the scientific evolution of sustainable building assessment methods. Sustainable Cities and Society, 49 (2019) 101610. https://doi.org/10.1016/j.scs.2019.101610.

1. Introduction

Since the 1970s, the performance evaluation and environmental assessment of buildings have generated intense research (Cole, 1998) in parallel with the development of the concept of sustainable building and motivated by the growing focus on the main agents involved. However, it was not until the 1990s that the construction sector began to recognise the significant impact of its activities on the environment (Haapio & Viitaniemi, 2008), the economy, public health (Darko et al., 2017) and well-being in cities (Macías & García Navarro, 2010). In fact, construction is currently one of the main reasons for accelerating climate change (de Klijn-Chevalerias & Javed, 2017).

To address this problem, in the last few decades, numerous SBAMs – tools that allow the grading and certification of the sustainability of the building and its surroundings in all phases of its life cycle (Haapio & Viitaniemi, 2008) have been developed. These methods, based on a series of indicators that measure different environmental aspects (Haapio & Viitaniemi, 2008), are based on a set of criteria that provide quantitative and qualitative performance, economic, social and usability indicators.

In the academic literature, numerous studies, based on different approaches and disciplines (industrial, social, economic, environmental, political, etc.), analyse the most common assessment methods; a large number of bibliographic reviews on sustainable building also exist. For example, Haapio and Viitaniemi (Haapio & Viitaniemi, 2008) performed a bibliographic review of 16 methodologies. Syahrul *et al.* (Kamaruzzaman et al., 2016) compared 10 methods based on the most commonly used assessments found in the literature and the accessibility of their manuals. Darko et al. (Darko & Chan, 2016) used the Scopus database to classify the main agents involved in ecological construction. Aarseth et al. (Aarseth et al., 2017) performed a systematic literature review and highlighted several sustainability strategies to improve building performance. Timothy et al. (Olawumi & Chan, 2018) performed a scientometric review of global research on sustainability and sustainable development. Marcio et al. (Thomé, Ceryno, et al., 2016) carried out a review and constructed a research agenda for sustainable architecture based on science mapping, where assessment methods appear as a satellite theme. Although that research reviewed 2096 bibliographic records, it focused on the concept of sustainable architecture as the main theme. No studies have been found that analysed evaluative tools while considering the different disciplines and approaches on which they are based. In addition, no other previous review has drawn a map of the relationships between studies on assessment methods, the concept of sustainable building and its main satellite themes.

The sustainability of a building and its assessment is a broad, complex and fragmented research field. The great diversity of disciplines and approaches involved make it impossible to obtain a single starting point that can be used to access this theme. In addition, not having a broad vision of the research area or the evolution of the themes in this field makes it difficult to obtain useful and unbiased information for future research. Therefore, comprehensive reviews that facilitate integrating these contributions and offer a critical perspective are needed.

To solve this problem, bibliometric analysis provides objective criteria for evaluating the work carried out by researchers (Noyons et al., 1999) and a macroscopic overview of large amounts of academic literature (van Nunen et al., 2018). The concept of bibliometric analysis was presented by Alan Pritchard in 1969, although bibliographic study in a particular field dates back to the 19th century (Osareh, 1996). This methodology has grown exponentially since the arrival of the internet, which has facilitated communication between researchers around the world and has allowed faster access to contributions in a given area (Roig-Tierno et al., 2017).

There are two main methods in bibliometric research: performance analysis and science mapping. While performance analysis aims to evaluate the impact of citations in the scientific production of different scientific agents, science mapping seeks to show the conceptual, social and intellectual scientific research structure and its evolution and dynamic aspects. These methods provide a spatial representation of how the disciplines, fields, specialties and documents or individual authors relate to one another (Small, 1999) by examining the bibliographic material from an objective and quantitative perspective (Albort-Morant & Ribeiro-Soriano, 2016). Many research fields use bibliometric methods to explore the impact of their field, of a group of researchers or of a particular document in order to show the structural and dynamic aspects of scientific research (Henderson et al., 2009).

The current objective of this chapter was thus to perform a bibliographic analysis of building sustainability assessment methods and sustainable building using a science mapping approach. To meet this goal, the following specific objectives were established:

(i) to perform a qualitative analysis based on a systematic review;

(ii) to perform a quantitative review using bibliometric analysis;

(iii) to analyse the results obtained from previous reviews.

This study will contribute to the existing body of knowledge by highlighting the trends and patterns in the research field of building sustainability and assessment, establishing its research themes, mapping researcher networks and recommending areas for future studies.

2. Material and methods

To achieve the objectives of this study, the double integrated analysis shown in Figure 1 was performed. It consists of (i) a systematic literature review (SLR) of the bibliographic records on building sustainability assessment methods and sustainable building and (ii) a review based on the bibliometric analysis of selected records. Each of these procedures is described in the following section.

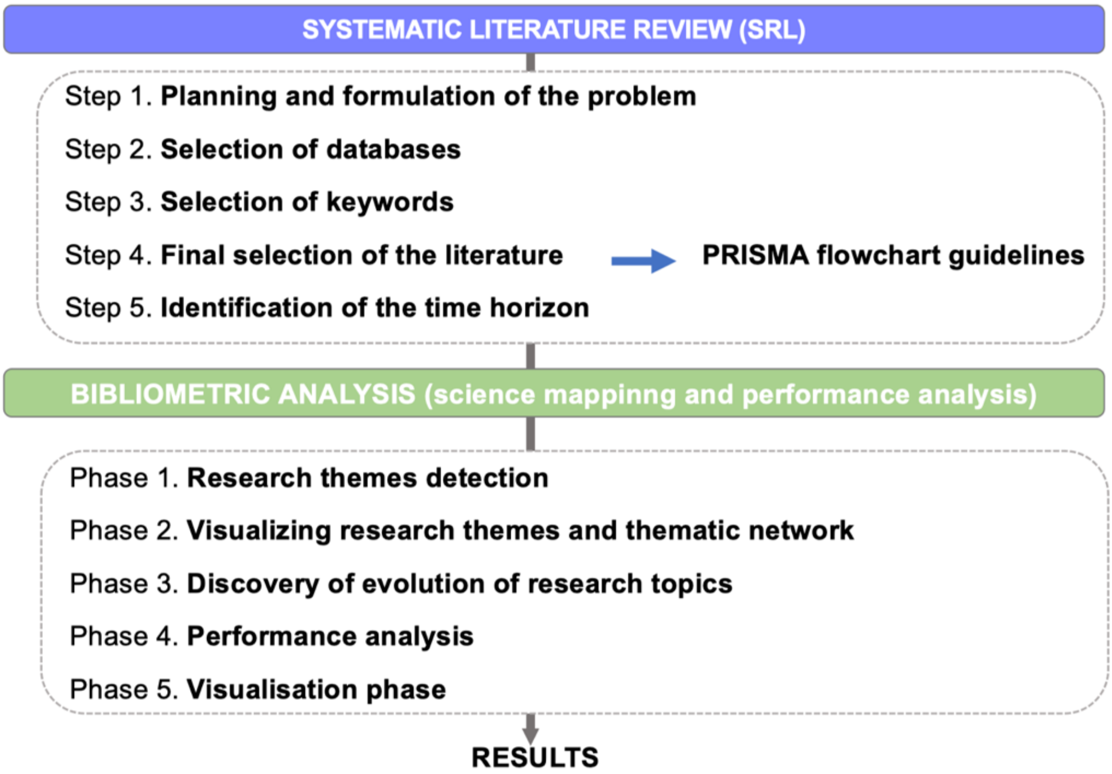


Figure 1. Materials and methods

2.1. Systematic literature review

To generate the SLR, a protocol is followed that defines the search strings and strategy, exclusion criteria, and methods for extracting data to synthesise the results. Therefore, the relevant body of literature was screened with clearly defined and understandable search options and with specific selection criteria (Ruhlandt, 2018). A large number of authors have implemented SLRs in their research, considering different stages with the aim of developing a replicable, scientific and transparent research process (Bhimani et al., 2018; S. Gupta et al., 2018; Polater, 2018; Ruhlandt, 2018; Savaget et al., 2019; Theisen et al., 2018). The objective of this approach is to avoid any possibility of bias or prejudice that may arise from applying pre-set criteria. In this paper, an SLR based on the guidelines contained in Thomé et al. (Thomé, Scavarda, et al., 2016) was carried out in the following stages (Figure 1):

(i) Planning and formulation of the problem. The first step in the SLR is planning and formulating the problem and setting the scope of the review. Establishing well–founded research questions is critically important for the next stages and researchers must therefore determine the inclusion and exclusion criteria for the final selection of relevant documents. The co-authors discuss the conceptualisation of the research field, propose research questions and define expected results.

(ii) Selection of the database(s). The second step is to define the most suitable bibliographic databases for the document search.

(iii) Selection of keywords. One of the most challenging aspects of bibliometric studies is the delimitation of keywords. The number of keywords should be large enough not to restrict the number of studies and specific enough to include only studies related to the subject. The search string is applied to obtain a first set of pre-selected records.

(iv) Final selection of the literature. This stage is essential to ensure that a considerable and manageable number of relevant documents are selected. The relevant documents are those that contain the necessary data to address the research questions in our SLR. In this stage, the relevant documents will be selected based on the PRISMA flowchart guidelines.

(v) Identification of the time horizon. Once the relevant documents are selected and the number of records per year is established, the time horizon is selected, as are the different periods. These are established according to various criteria, such as number of records, relevant items and turning points in the research field.

2.2. Biometric analysis

In recent years, innovative methods have been used to show the change and continuity of research over time (Cocosila et al., 2011). In this study, the bibliometric analysis was performed using Science Mapping Analysis Software Tool (SciMAT) software, a freeware science mapping tool that allows researchers to analyse the social, intellectual and conceptual evolution in a scientific field (Cobo et al., 2011; Oakleaf, 2009). SciMAT has been applied successfully in many areas, such as computer science, psychology, marketing and/or management, among others (Rodríguez-Bolívar et al., 2018).

This tool uses a series of scientific publications to build a knowledge base in which the identity of each publication and the different elements (keywords, journals, references, etc.) are stored (Cobo et al., 2011; Oakleaf, 2009). It is based on the analysis of co–words and the h–index (Hirsch, 2005) and incorporates methods, algorithms and measures for all steps in the workflow of general science mapping, from pre–processing to the visualisation of results (Cobo et al., 2011). SciMAT is based on the methodology defined by Cobo et al. (Cobo et al., 2012) and establishes the following four stages (Figure 2) that allow the analysis of a research field (Cobo et al., 2015):

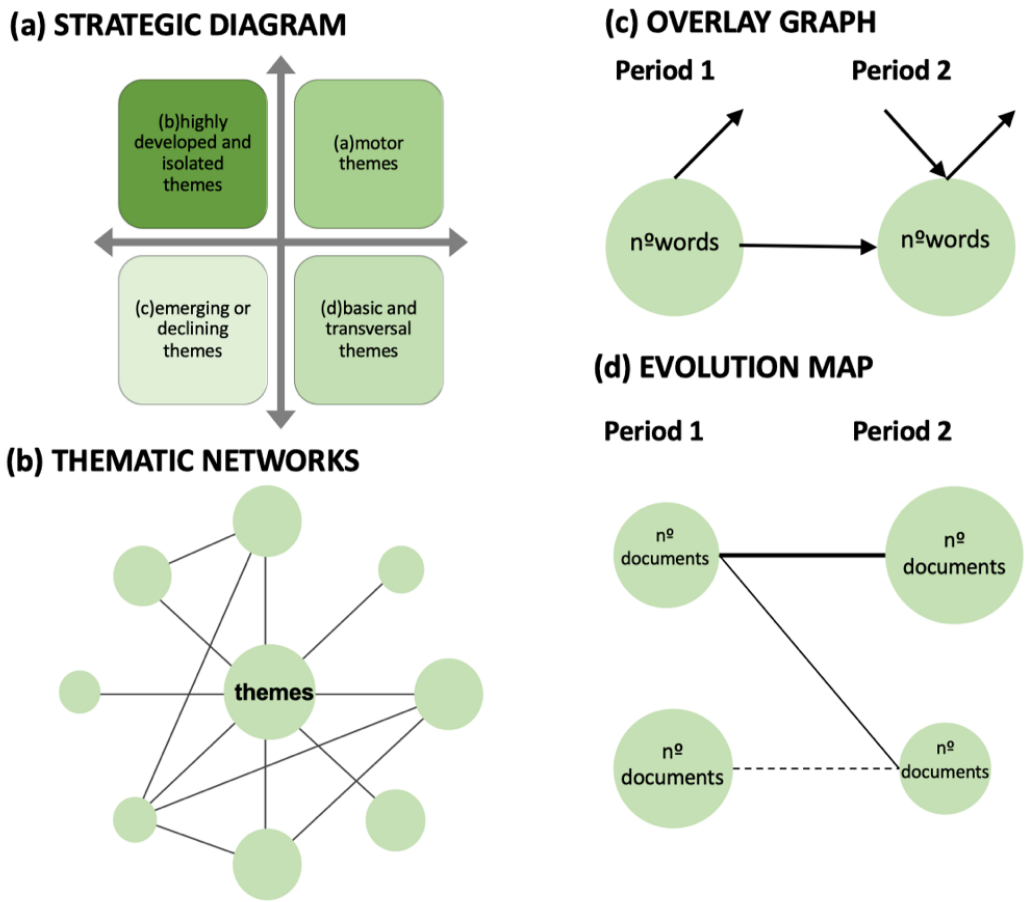


Figure 2. Example of a strategic diagram (a), thematic network (b), overlay graph (c) and evolution map (d)

(i) Detection of the research themes. To obtain research themes of great interest for the studies in each period, SciMAT firstly uses an equivalence index (Callon et al., 1991), which builds a standardised bibliometric network of keywords, and secondly applies the simple centre algorithm to cluster the keywords into themes.

(ii) Low dimensional space layout of research themes. In this second stage, the themes detected are displayed using two–dimensional strategic diagrams based on their centrality (degree of interaction of a research theme with other research themes) and density (internal strength value of the research theme) (Callon et al., 1991). A strategic diagram is divided into four quadrants (Figure 2a):

- Motor themes are in the upper–right quadrant. They are well–developed and important for the structure of the research field.
- Highly developed and isolated themes are in the upper–left quadrant. They are well developed but are of marginal importance for the research field.
- Emerging or declining themes are in the lower–left quadrant. They are poorly developed and marginally important.
- Finally, basic and transversal themes are in the lower–right quadrant. They represent important themes for the scientific field but are not well–developed.

As a complement to the strategic diagrams, the thematic networks show the relationship of each theme of the strategic diagrams with the keywords and their interconnections. Each thematic network is labelled using the name of the most significant keyword in the theme. Figure 2b shows an example of a thematic network. Here, several keywords are interconnected, where the size of the circle is proportional to the number of documents corresponding to each keyword, and the thickness of the link between two circles is proportional to the equivalence index.

(iii) Discovery of the evolution of research themes. At this stage, the evolving areas of the research field, their origins and inter-relationships are detected and analysed. The inclusion index (Sternitzke & Bergmann, 2009) is used to detect conceptual linkages between research themes in different periods and measure the strength of association between the themes. This analysis is represented by two graphs:

- Overlay graph (Figure 2c). The horizontal arrow represents the number of items shared by both time periods. The top entry arrow represents the number of new elements in period 2, and the top output arrow represents the elements shown in period 1 but not in period 2.
- Evolution map (Figure 2d). Solid lines indicate that related themes share a name, both themes having the same name, or the name of one of the themes being part of another one; a dotted line means that the themes share elements that are not the theme name. Finally, the line thickness is proportional to the inclusion index and the size of the circle is proportional to the number of documents associated with each theme.

(iv) Performance analysis. This analysis qualitatively and quantitatively measures the contribution of research themes to the entire research field by means of bibliometric measures such as number of published documents, number of citations and different variants of the h-index.

(v) Visualisation phase. Following the science mapping workflow, visualisation techniques are used to produce a scientific map and show the results of the different analyses.

3. Results

The method of SLR and bibliometric analysis described above was applied to perform an exhaustive analysis of the research field of building sustainability assessment methods and sustainable building, results that are reflected in the following sections.

3.1. A systematic literature review

Below the SLR methodology is described. It includes the definition of the research questions, the search process, the scope of the SLR (as defined by the inclusion and exclusion criteria), and how the data and corresponding search results were collected.

(i) Planning and formulation of the problem. The research questions were determined before starting the search. The SLR of this study addressed the following research questions: RQ1, What is the objective of this review?; RQ2, What is the status of this study field?;

RQ3: Who are the most prolific authors in the research field?; RQ4, What is the most influential work in the research field?; RQ5, What are the major themes in the research field?

(ii) Selection of the database. In this study, the ISI Web of Science (WoS) and Elsevier's abstract and citation database (Scopus) were selected due to the high number of international high impact scientific and technical publications they contain from all disciplines.

(iii) Selection of keywords. This review addressed two concepts: building sustainability assessment methods and sustainable building; therefore, it was necessary to ensure that both concepts were captured by keywords. An advanced search was performed using keywords related to both concepts as well as those satellite materials directly related to the research field. In addition, two search strings listed in Table 1 were included. The search was performed using the field "Title/Abstract/Keyword" through the inclusion of the terms indicated, as well as the inclusion of the keywords "sostenib*" (sustain*) and "edific*" (build*) (to detect any words beginning with "sustain" or "build").

Table 1. Keyword search strings

concepts	Keyword search strings
SBAM	"assessment methods", "assessment tools", "assessment systems", "indicators", "environmental impact", "social impact" and "economic impact"
sustainable building	"environmental impact", "social impact" and "economic impact"

(iv) Final selection of the literature. After using the selected keywords and search strings to search the Scopus and ISIWoS databases, the records obtained were collected and filed. Once the previous records had been compiled, we applied the PRISMA flowchart guidelines (Figure 3), where the number of relevant documents finally identified is shown.

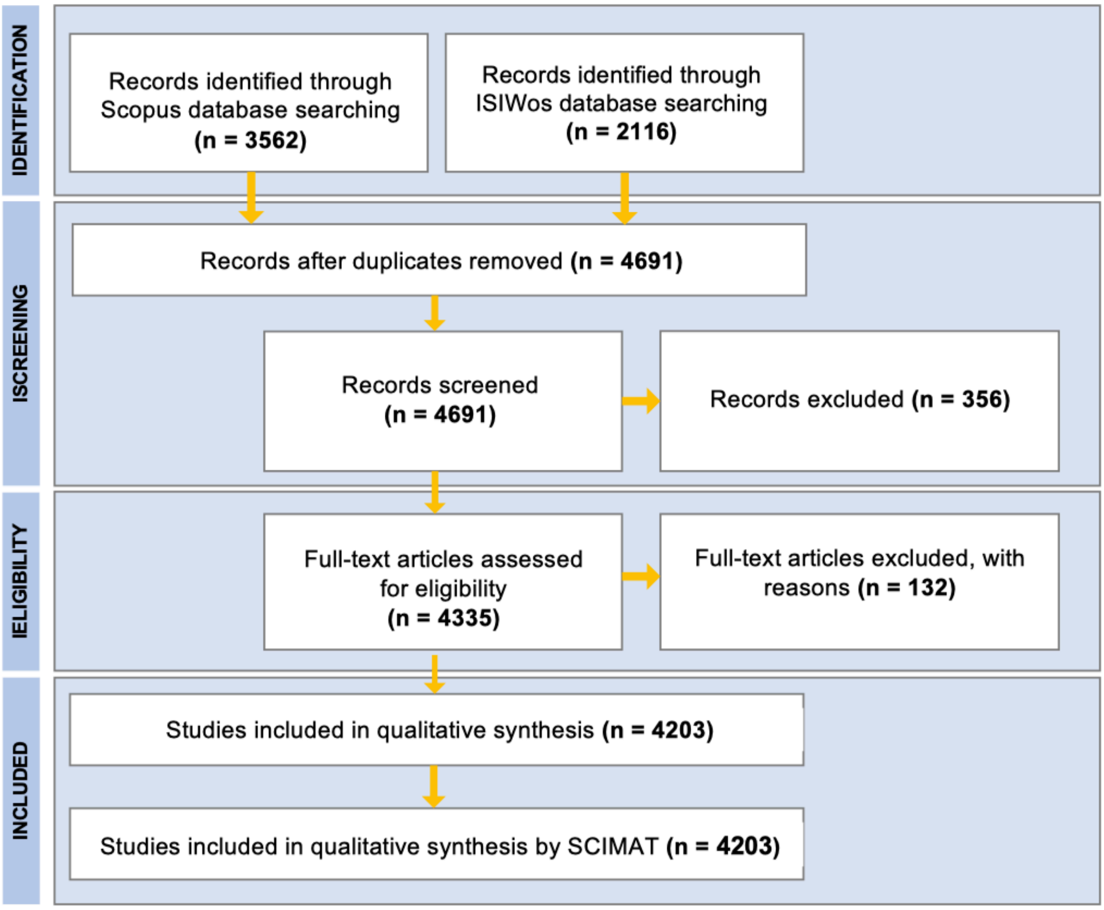


Figure 3. PRISMA flowchart guidelines

A total of 5678 bibliographic records were retrieved from the two selected databases. After eliminating 987 duplicates, 356 of the remaining 4691 records were excluded by analysing the title and summary and applying the defined exclusion criteria. A full text examination was done of the remaining 4335 records and 132 additional records were excluded since they did not cover the topics included in this review. This left 4203 relevant documents for the study.

(v) Identification of the time horizon. The time horizon was determined based on the main milestones and inflection points of the evolution of sustainable building and its assessment. Since the first attempts to assess the environmental performance of buildings took place in the 1970s (Cole, 1998), the time horizon used in this study was from 1975 to 2017. It was then subdivided into the following 4 periods, taking into account the number of documents selected as well as relevant milestones in order to analyse the trends in publication patterns.

- **First period (1975–1989):** In the 1970s, the concept of sustainable building emerged, with special emphasis on energy conservation and efficiency. This was the beginning of research into assessment methods that looked at technologies that achieved more efficient energy performance (Macías et al., 2010).

- **Second period (1990–1999):** In the 1990s, and coinciding with the launch of the Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom in 1990 and the creation of the United States Green Building Council (GBC) in

1993, there was extensive development of environmental assessment methods as effective instruments to achieve substantial reductions in the environmental impacts produced by buildings (Cole, 2006; Todd et al., 2001). Special emphasis was placed on the impact of material manufacturing on the natural environment. An important milestone in this research field was the Kyoto Protocol, adopted in December 1997 in Kyoto and driven by the UN (United Nations, 1998) as a response to the threat posed by climate change. It provided a set of measures aimed at reducing GHG emissions compared to 1990 levels.

- **Third period (2000–2009):** From the year 2000, coinciding with the expanding application of the Leadership in Energy and Environmental Design (LEED) rating system, numerous assessment methods began to emerge. This significant increase can be attributed to the growing recognition of sustainable architecture by industries and construction authorities around the world, as well as to the pioneering methodologies that were becoming widely accepted. As examples, the Green Standard for Energy and Environmental Design (G-SEED) in 2001 in South Korea, the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in 2002 in Japan, and the Green Building Tool (GBTool) in Canada.

- **Fourth period (2010–2017):** Finally, in the last period and coinciding with Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, there was a marked increase due to concern over sustainable building assessment, which was in turn reflected by an increase in research in this field.

3.2. Bibliometric analysis. Science mapping

After the SLR was performed, 4203 documents were obtained that had been published within the time horizon (1975–2017). Finally, the following configuration in SciMAT for the bibliometric analysis was established: word as the unit of analysis, analysis of co-occurrence as the tool to build the networks, index of equivalence as the measure of similarity to standardise the networks, and the k–means clustering algorithm to detect the themes. Documents were analysed by year of publication, journals used, authors, and number of citations. The results obtained are summarised below.

3.2.1. Documents per year

In Figure 4, the distribution of 4203 publications by year is shown. An irregular distribution in the number of relevant articles published annually is observed, and the number is not typically high, with the exception of 2017, in which the number of published studies was more than double that of the previous year.

Before 2012, there were fewer than 156 publications per year related to this research field, except for 1999, where a peak can be seen coinciding with adoption of the Kyoto Protocol in 1997 (United Nations, 1998). This agreement led the main developed countries and transitioning economies to adopt legally binding commitments to reduce or limit greenhouse gas emissions. Since 2012, there has been a constant increase in the number of articles, demonstrating the attention given in recent years to assessment methods, which have become a vital part of sustainable building research.

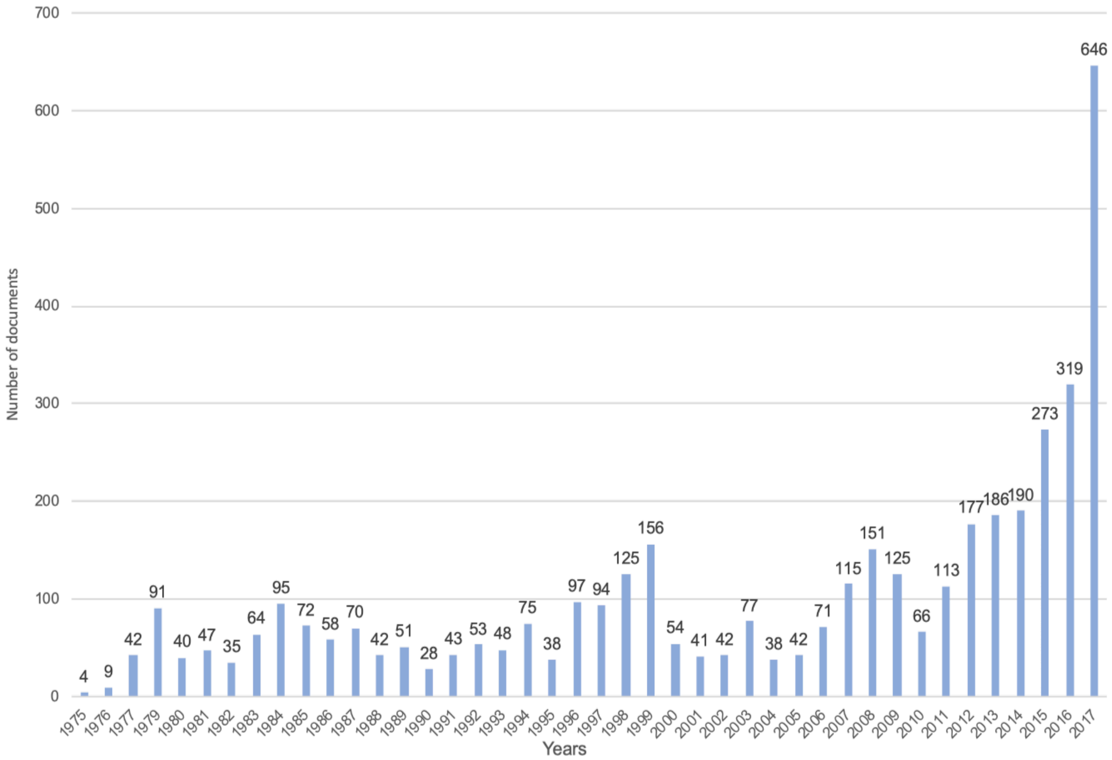


Figure 4. Documents per year

3.2.2. Documents by journal

565 journals were identified in the study. Table 2 shows the publications for 20.07% of the documents analysed, which are ranked in descending order by the number of citations. Most of them are research journals focusing on energy use and efficiency in buildings, the science of

their construction, human interaction with the interior and exterior of built environments, and environmentally sustainable buildings and cities.

Table 2. Main publications contributing to the research field.

publications		**document**			
name	citation	number	most cited	citation	reference
Energy and Buildings*	5451	175	Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept	184	(Feist et al., 2005)
Building Research and Information*	4300	114	Are users more tolerant of 'green' buildings?	165	(Leaman & Bordass, 2007)
Building and Environment*	3186	163	Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification	301	(Zabalza Bribián et al., 2009)
Landscape and Urban Planning	1885	38	Applying landscape ecological concepts and metrics in sustainable landscape planning	478	(Botequilha Leitão & Ahern, 2002)
Journal of Cleaner Production*	1569	163	Advancing sustainable urban transformation	126	(McCormick et al., 2013)
Energy Policy	1247	32	Environmental impacts of energy	175	(Dincer, 1999)
Applied Energy	973	44	Towards sustainable-energy buildings	168	(Chwieduk, 2003)
Energy	727	36	Impact of climate change on energy use in the built environment in different climate zones - A review	114	(D. H. W. Li et al., 2012)
Renewable Energy	641	63	Evaluation of the cost efficiency of an energy efficient building	25	(Gieseler et al., 2004)
Sustainable Cities and Society	340	35	Sustainable building assessment tool development approach	69	(Alyami & Rezgui, 2012)

*publications with the largest number of documents

Table 2 also includes the most frequently cited document in each journal. As shown, the numbers of publications and citations are not closely related because only four of the major journals (identified in Table 2 with an*), in terms of number of articles, are also ranked among the top five in number of citations. In other words, the most prolific sources have not necessarily been those with the greatest impact in the research field.

3.2.3. Documents by author

The SRL allowed the identification of 8581 authors who have published articles dealing with the topic of the study. Table 3 shows those authors with more than ten published studies, sorted by total number of documents published; it also incorporates the number of citations received, as well as the h-index (Hirsch index), a measure of the authors' professional quality according to the number of times that their scientific articles have been cited (Schreiber, 2015). According to the analysis, J. Kurnitski has published the most articles on the topic of building sustainability assessment methods; however, Li et al. has the highest index for the number of citations. It should be noted that M. Santamouris has the highest h–index.

Table 3 also contains the most-cited document for each author, along with the keywords and the number of citations. As shown, a close relationship between the number of publications and the total number of citations does not exist, since only two of the top authors in number of documents are ranked among the top five in number of citations. Regarding keywords, it should be noted that the concepts of energy, Zero Energy Building (ZEB) or net Zero Energy Building (nZEB) are the most frequent among the authors, in addition to the assessment methods, CASBEE, LEED and BREEAM.

Table 3. Authors with more than ten published studies in the research field.

name	n[a]	c[b]	h-Index	most cited document	c[c]	reference
Kurnitski, J.	16	281	19	Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation	127	(Kurnitski et al., 2011)
Murakami, S.	14	60	6	Development of a comprehensive city assessment tool: CASBEE-City	28	(Murakami et al., 2011)
Ikaga, T.	13	38	6	Development of a comprehensive city assessment tool: CASBEE-City	28	(Murakami et al., 2011)
Santamouris, M.	12	573	60	Heat island research in Europe: The state of the art	180	(Santamouris, 2007)
Kalamees, T.	11	175	18	Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA 6definition for nZEB national implementation	127	(Kurnitski et al., 2011)
Wang, X.	10	41	25	A decade review of the credits obtained by LEED v2.2 certified green building projects	20	(Wu et al., 2016)
Carlucci, S.	10	161	11	Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design	135	(Attia et al., 2013)
Rezgui, Y.	10	167	27	Sustainable building assessment tool development approach	69	(Alyami & Rezgui, 2012)
Attia, S.	10	175	10	Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design	133	(Attia et al., 2013)

[a] numbers of documents per author
[b] numbers of citations per author
[c] numbers of citations per document

3.2.4. Most cited documents

The systematic literature review ended with the study of the most-cited documents. The 4203 documents analysed received 52582 citations. Table 4 lists the five publications with the greatest number of citations, a total of 2147, which accounts for 0.038% of the total.

Table 4. Most cited documents.

title	publication	year	n[a]	%[b]	reference
Adaptive thermal comfort and sustainable thermal standards for buildings	Energy and Buildings	2002	669	0.012	(Nicol & Humphreys, 2002)
Sustainable construction-The role of environmental assessment tools	Journal of Environmental Management	2008	472	0.008	(Ding, 2008)
Sustainable development and climate change initiatives	Cement and Concrete Research	2008	385	0.007	(Damtoft et al., 2008)
A critical review of building environmental assessment tools	Environmental Impact Assessment Review	2008	320	0.006	(Haapio & Viitaniemi, 2008)
Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification	Building and Environment	2009	301	0.005	(Zabalza Bribián et al., 2009)
Total			2147	0.038	

The most cited documents focus on different aspects of the thematic field analysed, revealing its diversity. These works range from the evolution of green building and the implementation of Life Cycle Assessment (LCA) in the construction sector to exhaustive reviews of the most common SBAMs.

3.3. Content analysis

3.3.1. Strategic diagrams

To analyse the changes over time, strategic diagrams (shown in Figure 5–8) were generated for the four periods considered (1975–1989, 1990–1999, 2000–2009, and 2010–2017), where the size of the circle is proportional to the number of published documents associated with each research theme. In addition, Tables 5–8 shows performance measures obtained for each theme and period in terms of number of documents, h-index, and values of centrality and density. An analysis of the results obtained for each period is shown below.

3.3.1.1. First period

Table 5. Performance analysis by period 1 (1975–1989).

	Name	No. of documents	No. of citations	h-Index	Centrality	Density
1	Enviromental assessment tool	37	154	8	23.48	12.52
2	Residential building	97	88	5	38.92	43.23
3	Life cycle cost	13	9	2	12.78	6.45
4	Environmental impact	19	47	4	37.49	11.06
5	Rating system	8	6	2	10.31	35.09
6	Energy resources	9	103	3	14.66	17.71
7	Passive house	19	12	2	11.62	2.88
8	Office buildings	4	1	1	2.22	2.26

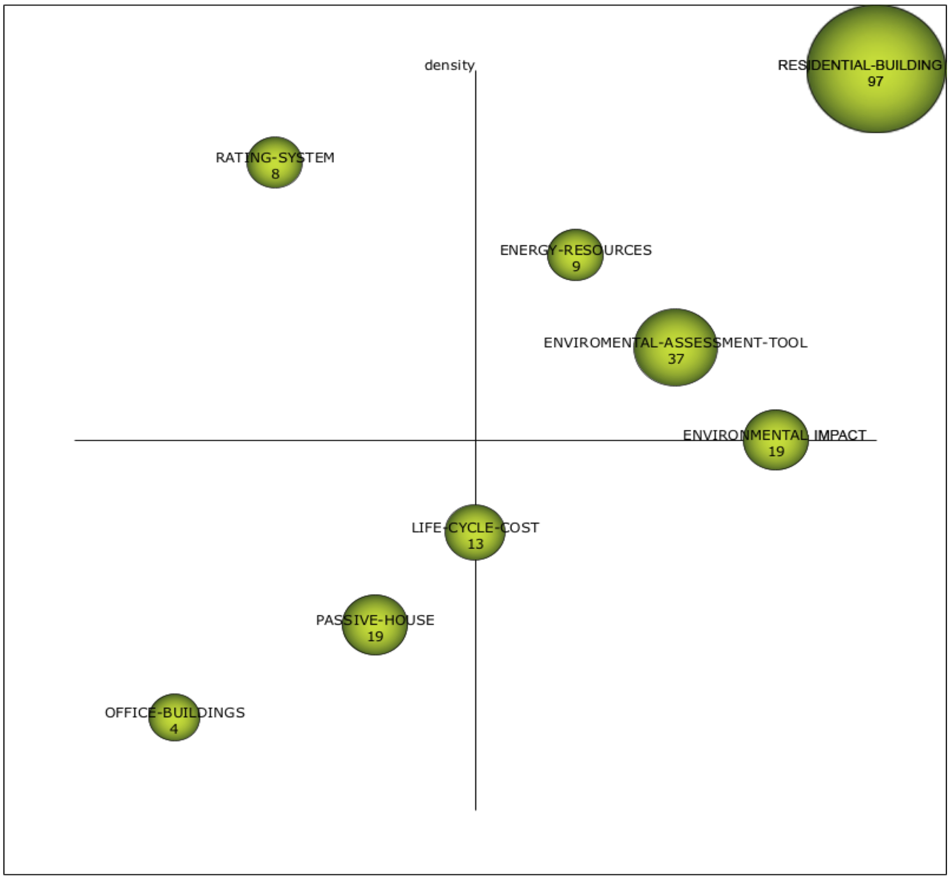


Figure 5. Strategic diagrams by period 1.

First period (1975–1989). According to the strategic diagram presented in Figure 5, 8 research themes can be observed in the 720 papers selected in this period: environmental assessment tools, residential buildings, life-cycle cost, environmental impact, rating systems, energy resources, passive houses, and office buildings. Of these, 3 were considered motor themes (environmental assessment tools, residential buildings and energy resources), 1 a highly developed and isolated theme (rating systems), 2 emerging or declining (passive houses and office buildings) and finally, 2 others were considered basic (life–cycle cost and environmental impact).

The performance analysis for each theme, as shown in Table 5, complements the information provided by the diagram that highlights how the two themes that present the highest performance measures are "environmental assessment tools" and "environmental assessment tools". These themes attain a high impact rate and account for more than a thousand citations, also obtaining a higher h–index than the remaining themes. Environmental assessment tools are designed to assess different types of buildings and emphasise different stages in the life cycle (Haapio & Viitaniemi, 2008), but in this period these tools focused on products and not so much on buildings.

3.3.1.2. Second period

Table 6. Performance analysis by period 2 (1990–1999).

	Name	No. of documents	No. of citations	h-Index	Centrality	Density
1	Energy efficiency	8	46	5	31.25	35.88
2	GHG emissions	5	58	4	34.74	69.07
3	Life cycle cost	43	865	16	59.43	10.45
4	Construction material	17	271	8	102.36	24.19
5	Building design	20	356	7	54.84	13.44
6	Environmental impact assessment	50	1,616	21	78.23	8.48
7	Renewable energies	73	2,075	18	29.4	17.3
8	Developing countries	13	233	8	37.89	14.86
9	Rating system	17	1,003	13	32.77	10.72
10	Natural resources	12	847	5	28.62	5.39
11	Green building	20	278	9	49.44	2.92
12	Heat losses	6	325	3	44.48	12.93

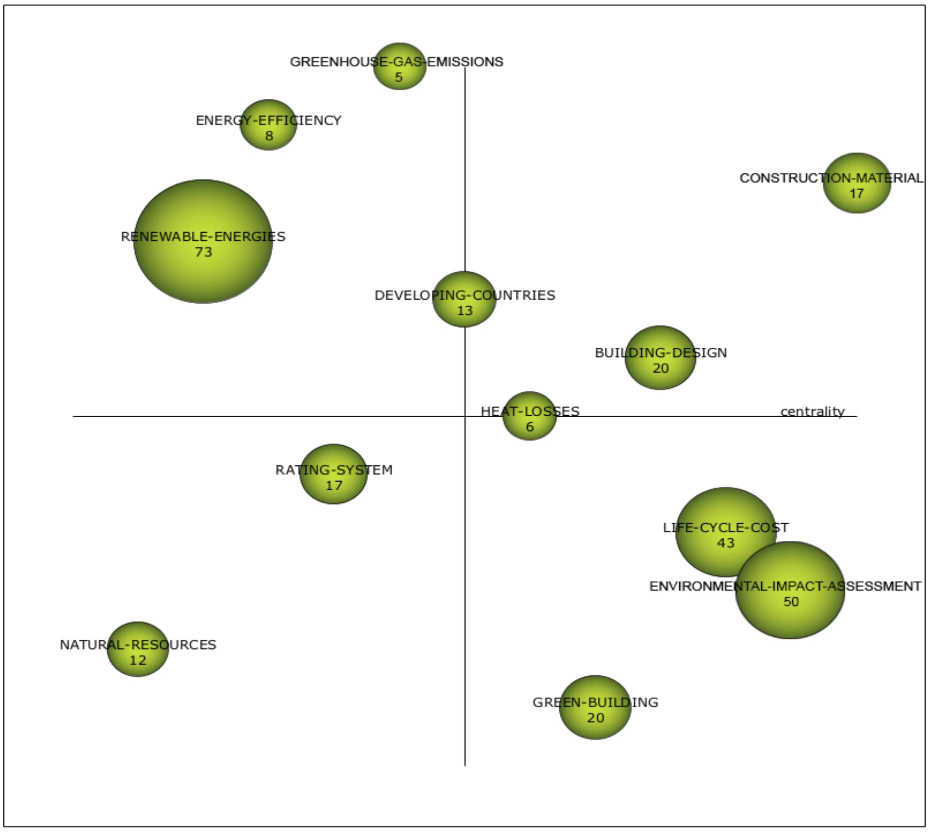


Figure 6. Strategic diagrams by period 2.

Second period (1990–1999). According to the strategic diagram presented in Figure 6, in the 756 papers selected in this period, 12 research themes can be observed. Four of these themes were considered motor themes (construction materials, building design, developing countries and heat loss), 3 highly developed and isolated themes (energy efficiency, GHG emissions and renewable energies), 2 emerging or declining (rating systems and natural resources) and, finally, 3 basics (environmental impact assessment, life–cycle cost and green building).

In accordance with the performance measures (Table 6), the following 3 themes can be highlighted: life–cycle cost, environmental impact assessment and rating systems. These research themes had a high impact rate and also achieved a higher h–index than the remaining themes. Within the context of the construction industry, life–cycle cost is a method used to assess the anticipated economic performance of a building throughout its life cycle, which includes design and construction, operation and maintenance, and disposal (J.W. Bull, 1992). A green building rating system provides the project team with a framework and a tool to help achieve better sustainable development (Awadh, 2017).

3.3.1.3. Third period

Table 7. Performance analysis by period 3 (2000–2009).

	Name	No. of documents	No. of citations	h-Index	Centrality	Density
1	SBAM	590	16947	69	126.26	0.82
2	LEED	9	84	5	33.99	1
3	Heating	43	1714	20	40.53	0.55
4	BREEAM	26	847	15	33.94	0.64
5	Co_2 emissions	34	773	12	37.57	0.27
6	Intelligent buildings	25	488	7	31.46	0.73
7	Green building	27	623	11	19.8	0.45
8	Energy	36	988	17	33.57	0.09
9	Natural resources	16	597	7	18.41	0.18
10	Economic aspect	12	258	7	13.8	0.36
11	LCA	3	200	3	1.2	0.91

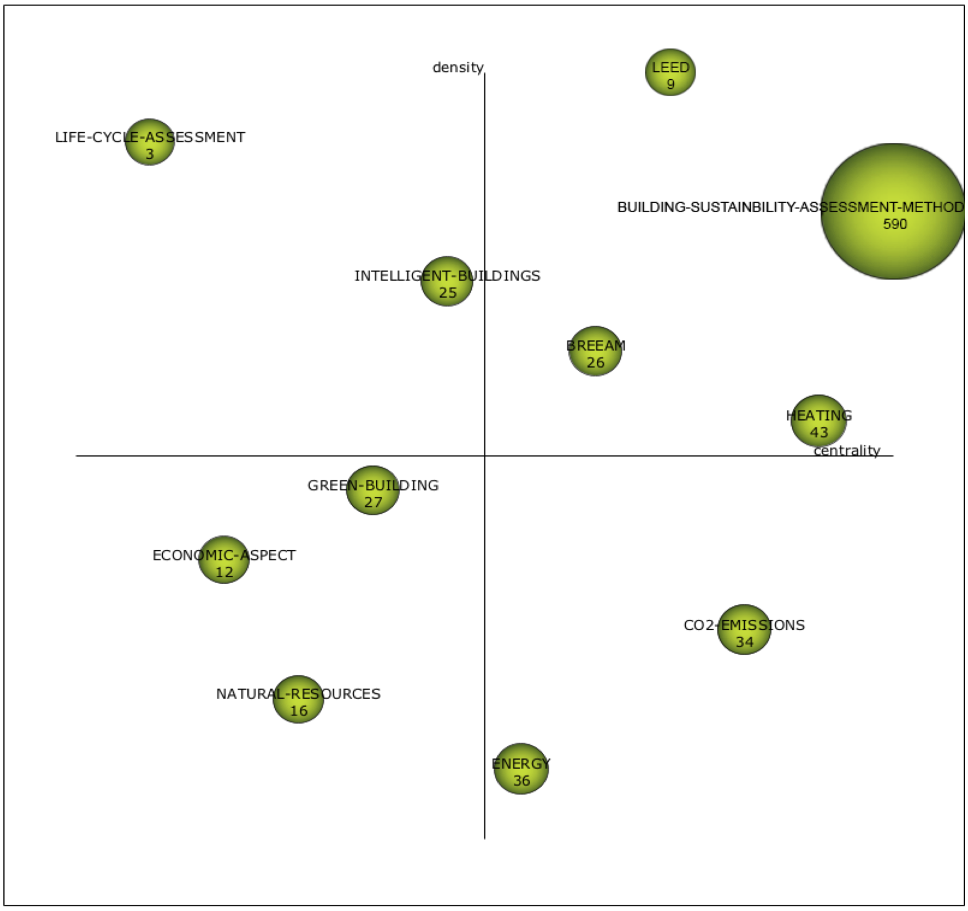


Figure 7. Strategic diagrams by period 3 .

Third period (2000–2009). According to the strategic diagram presented in Figure 7, in the 756 papers selected in this period, 11 research themes can be observed: SBAM, LEED, heating, BREEAM, CO_2 emissions, intelligent buildings, green building, energy, natural resources, economic aspects and LCA. Three of these were considered motor themes (SBAM, LEED, heating and BREEAM), 2 highly developed and isolated themes (life-cycle assessment and intelligent buildings), 2 emerging or declining (economic aspects, natural resources and green building) and finally, 2 others were considered basic (CO_2 emissions and energy).

In accordance with the performance measures, the following 3 themes can be highlighted: building sustainability assessment methods, heating and energy. These research themes obtained a high impact score and also attained a higher h–index than the remaining themes. The themes heating and energy are closely related topics. Energy use in buildings forms a large part of global and regional energy demand. The importance of heating and cooling in total building energy use is very diverse varying between 18% and 73% of the total (Ürge-Vorsatz et al., 2015).

3.3.1.4. Fourth period

Table 8. Performance analysis by period 3 (2010–2017).

	Name	No. of documents	No. of citations	h-Index	Centrality	Density
1	Sustainable building	1122	11574	46	148	41.32
2	LEED	140	3133	22	45.25	9.83
3	Heating	172	2147	26	60.53	9.45
4	Urban development	316	2407	25	36.55	9.37
5	Life cycle cost	103	863	13	35.55	7.74
6	Indoor environmental quality	56	314	8	21.31	7.55
7	Construction material	81	660	10	17.9	8.63
8	Environmental impact	71	649	14	36.83	1.95
9	Energy efficiency	17	51	4	3.97	7.72
10	Passivhaus standard	16	95	6	9.82	1.58
11	Building simulation	7	137	4	5.31	2.42
12	Social aspect	9	132	5	5.16	3.28

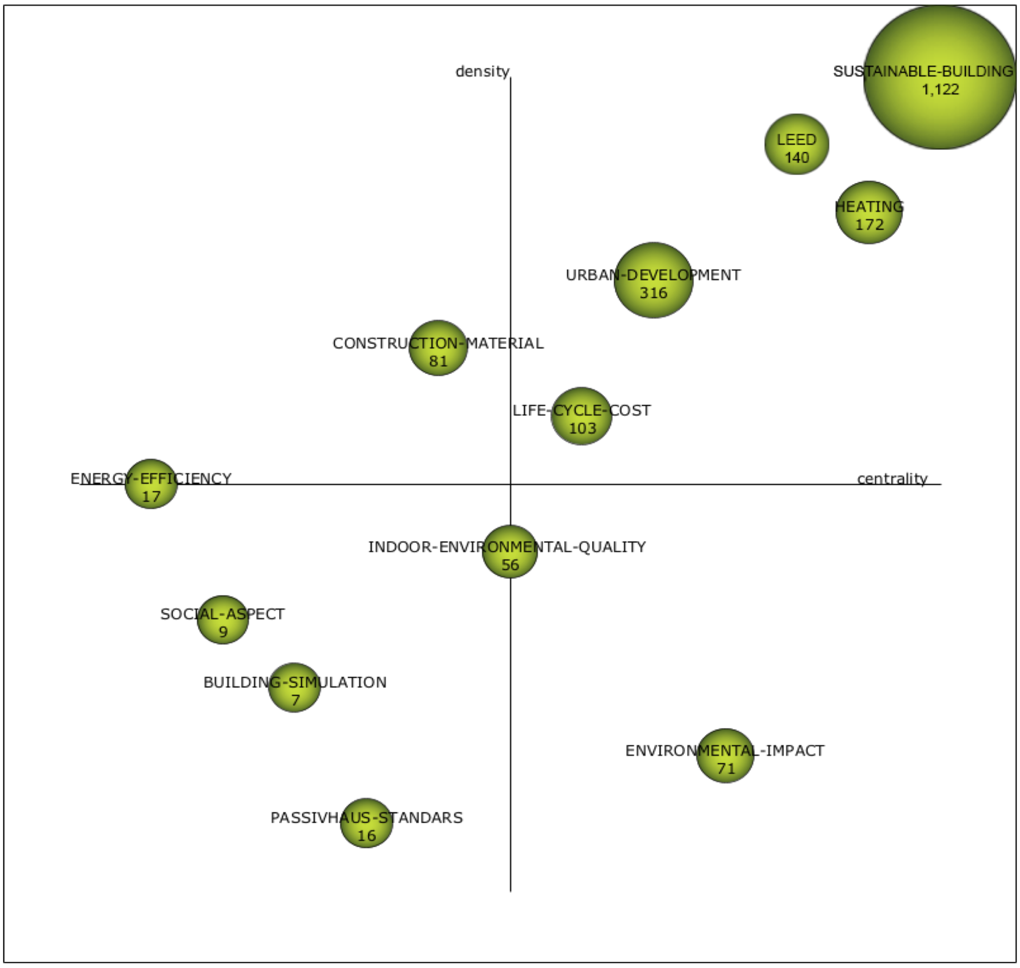


Figure 8. Strategic diagrams by period 4.

Fourth period (2010–2017). According to the strategic diagram presented in Figure 8, in the 756 papers selected in this period, 12 research themes can be observed: sustainable building, LEED, heating, urban development, life-cycle cost, indoor environmental quality, construction materials, environmental impact, energy efficiency, Passivhaus standard, building simulation and social aspects. Five of these were considered motor themes (sustainable building, LEED, heating, urban development and life-cycle cost), 2 highly developed and isolated themes (construction material and energy efficiency), 3 emerging or declining (Passivhaus standard, building simulation and social aspects) and finally, 2 others were considered basic (indoor environmental quality and environmental impact).

In accordance with the performance measures (Table 8), the following four themes can be highlighted: sustainable building, LEED, heating and urban development. These research themes obtained a high impact score and also achieved a higher h-index than the remaining themes. It should be noted that the emerging theme social aspects appears in this period with modest performance indicators, but it is the baseline for important themes in the future.

3.3.2. Thematic network

The sustainable building theme of the last period is worthy of mention as one of the most characteristic themes if it is analysed from the point of its thematic network.

Thus, in Figure 9, we can observe that the already consolidated sustainable building theme in the last period is closely linked to keywords such as nZEB, intelligent buildings, building design and climate change. These are all closely related to each other and, in recent years, have been the focus of numerous studies. This indicates where the sustainable building assessment research field is heading, with an emphasis on the study of climate change in relation to the design and consumption of buildings.

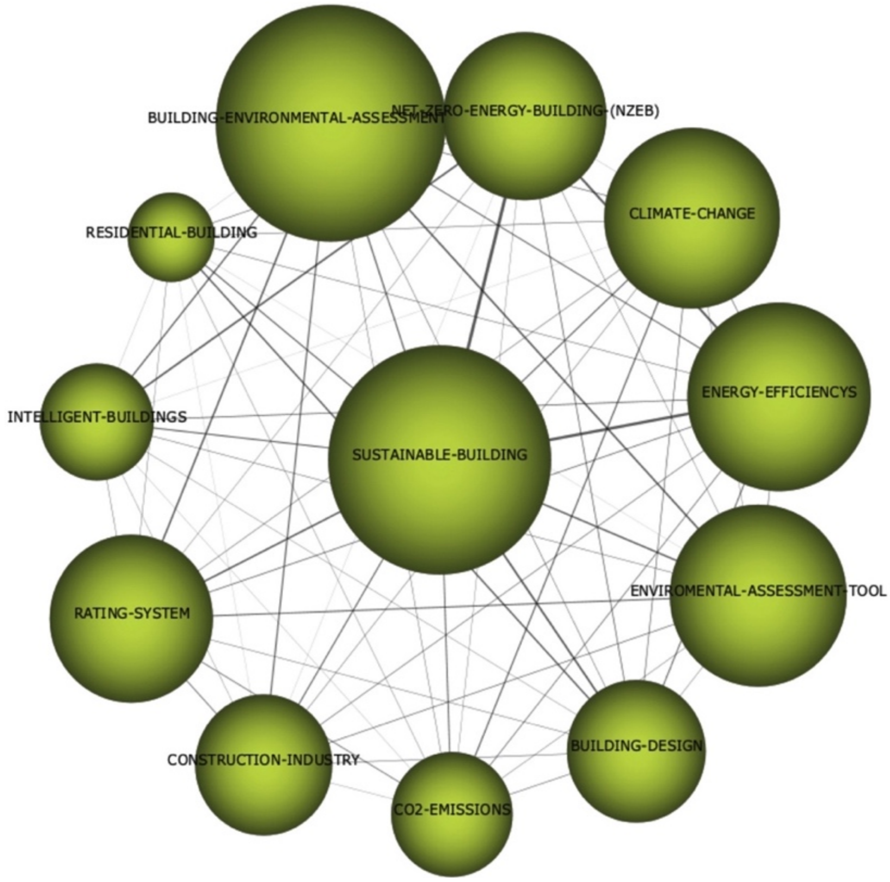


Figure 9. Thematic network

3.3.3. Conceptual evolution map

The systematic literature review showed that a very large number of authors, journals and documents deal with the research field of assessment methods and sustainable building. Nonetheless, the strategic diagrams reflect the interest of the scientific community in certain key issues, in parallel with the development of the concept of sustainable building. In the early years, the review demonstrates the concern regarding the environmental impact generated by the buildings themselves, specifically residential buildings, without considering the social and economic aspects of sustainability. In the 90s, life–cycle cost, construction materials and renewable energy, including an interest in the economic aspect of sustainability by the main authors, drew the attention of the largest number of documents. From the year 2000, a great interest was shown in the two main methods used for building sustainability assessment, LEED and BREEAM. More recently, interest has focused on sustainable building and urban development. For this reason, a joint analysis of the evolution of keywords and the thematic evolution of the research field would be interesting. The results are shown in Figure 10ab.

Figure 10a represents the number of keywords per period and their evolution, as well as the number of outgoing and incoming keywords, and the number and percentage of keywords that are retained from one period to the next. The number of keywords clearly grows throughout the periods, in parallel with the increase in document numbers over the years. The number of keywords increases from 179 to 944 between the first and last periods, a 527% growth rate. Specifically, out of 179 keywords that appeared in the first period, 49% (88) remain in the second period, and 155 words are added, giving a total of 243 words. In the third period, 188 words remain (77%), and 301 new words are included, representing a total of 489. Finally, in the fourth period, 421 (86%) keywords from the third period remain, and 523 new keywords appear, resulting in a total of 944. These results indicate that the number of new and transitional keywords is high but also that the number of keywords shared by successive periods has increased. Therefore, the growing thematic diversity of the research field of sustainable building assessment and the fact that the keywords reappeared with increased strength in the following periods could be indicators that this relatively new research field is gradually being consolidated.

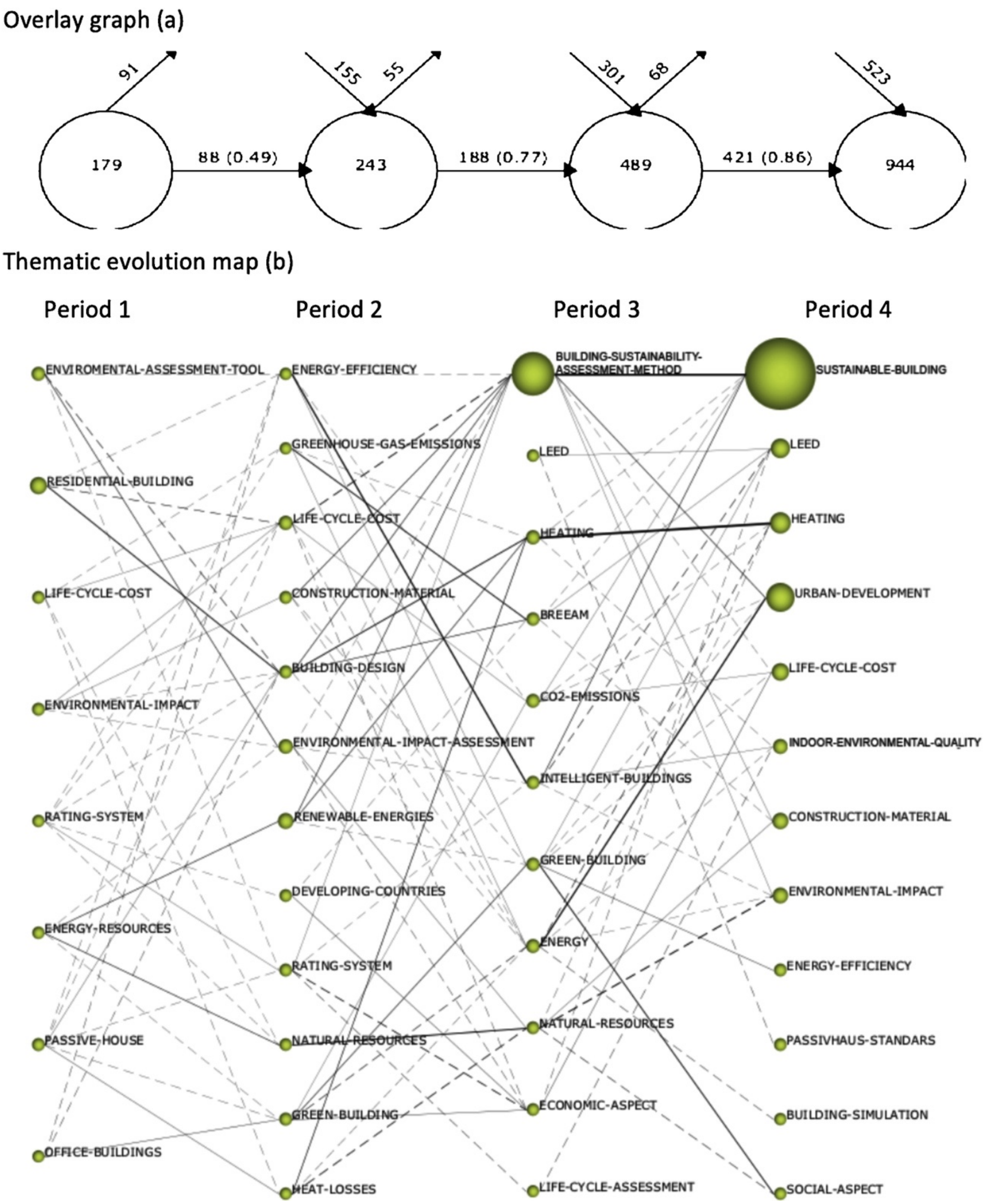


Figure 10. Overlay graph (a) and thematic evolution map (b) of the research field by periods.

Finally, Figure 10b shows the thematic evolution of the research field through the analysis of the themes' origins and inter–relationships. The thickness of the lines represents the strength of the association measured by the inclusion index. If the graph is analysed from the point of view of the number of documents, residential building appeared with the largest number of core documents in 1975–1989; it evolved into the themes of energy efficiency, life–cycle cost and building design in 1990–1999. Renewable energies appeared with the largest number of core documents in 1990–1999; it evolved into the themes of building sustainability assessment methods, CO_2 emissions, intelligent buildings and green buildings in 2000–2009. Building sustainability assessment methods appeared with the largest number of core documents in 2000–2009; it evolved into the themes of sustainable building, urban development, life-cycle cost, construction material and environmental impact.

It should be noted that the life cycle cost thematic cluster from 1975 to 1989 continued to use the same label in 1990–1999. However, the number of core documents published on the theme increased and it merged with building sustainability assessment methods, CO_2 emissions, energy and economic aspects. It appeared again in the last period, with the largest number of documents, which shows that life–cycle cost is gaining considerable attention, particularly within the context of sustainable construction (Dwaikat & Ali, 2018). In the construction sector, it is used to compare different design alternatives for a building or a system, considering the life–cycle cost and saving associated with each design option, which explains its relationship with the building sustainability assessment method thematic cluster and the economic aspects thematic cluster. However, the application of life–cycle cost in the construction sector is still limited and is facing practical problems (Dwaikat & Ali, 2018). According to Botelho et al. (Botelho et al., 2017) determining the economic value of environmental impacts is not a simple process, since there are no markets for the environmental goods and services impacted and, therefore, prices are not available. The rating system thematic cluster from 1975 to 1989 also continued with the same label in 1990–1999, but with a larger number of core documents published on the theme and it merged with building sustainability assessment methods, intelligent buildings, economic aspects and life–cycle assessment.

Finally, the green building thematic cluster from 1990 to 1999 continued to have the same label in 2000–2009, but with a larger number of core documents published on the theme. It merged with LEED, urban development, energy efficiency and social aspects, since these topics are closely related. Although there are several terms and meanings associated with what it is to be a green building, they are expected to have a reduced impact on the natural environment and create a more resource–efficient model with regard to building–related practices (Prum, 2010). Green buildings, however, do not only address issues related to ecological protection; they also address issues related to social justice, public health, and productivity (Cidell & Beata, 2009).

4. Conclusions

The systematic literature review shown is based on the use of SciMAT for the bibliometric analysis of the evolution of the selected research field between 1975 and 2017, using the publications available through the ISIWoS and Scopus. Trends were analysed, considering an overview and a more specific analysis of four different time intervals during the period under review (1975–1989, 1990–1999, 2000–2009, and 2010–2017).

The analysis has shown that building sustainability assessment methods and sustainable building are significant themes, especially over the last five years, with a gradual increase in the number of studies on these topics published in international journals since 2012. Overlay graphs by periods have shown two main problems: (i) the greater number of new and transitory keywords between sub–periods, a sign that this is a field of research in constant evolution that has not yet reached a stage of maturity; and (ii) an evolutionary trend in each of the research topics in the field analysed.

Strategic diagrams and performance analysis by period also show that emerging studies focus on the inclusion of social and economic aspects. In the early years (from 1975 to 1989), there is a clear concern about the environmental impacts generated by buildings, specifically residential buildings, but not about the social and economic aspects of sustainability. In the 90s, the largest number of documents focused on life–cycle cost, construction materials and renewable energy, including a greater interest in the economics of sustainability by the most prolific authors. Since the year 2000, there has been great interest in the main building sustainability assessment methods, LEED and BREEAM, according to the studies. Finally, recently (2010–2017), interest has focused on sustainable buildings and urban development.

It can be seen how the evaluation instruments have evolved from tools that only looked at environmental aspects towards more complete instruments that include economic and social aspects in the evaluation of building sustainability. This is clearly reflected in the last period where environmental impacts are the basic, crosscutting issue, social aspects are emerging issues, and life cycle cost is positioned as a motor theme.

The previous findings show that this study is a valuable contribution to research concerning building sustainability assessment methods and sustainable building, because it provides researchers and professionals in the field with a detailed understanding of the status quo and predicts the dynamic directions of this field.

CHAPTER 2

Comparative analysis of sustainable building assessment methods [2]

[2] The results shown in this chapter were presented in: C. Díaz-López, M. Carpio, M. Martín-Morales, M. Zamorano. A comparative analysis of sustainable building assessment methods. Sustainable Cities and Society. 49 (2019) 101611. https://doi.org/10.1016/j.scs.2019.101611.

1. Introduction

The systematic literature review and scientific mapping of the field of SBAMs research have shown that new methods are continuously being proposed, and the most widely used ones are updated on an annual basis; in fact, countries around the world have developed many methods, more than 600 in total, along with the rapid development of sustainable buildings (Doan et al., 2017). Examples of this include assessment methods such as BREEAM, HQE, Verde, Protocollo ITACA, PromisE, Økoprofil, Nordic Swan, Lider A, DGNB; standards, including Passivhaus standar, Built Green and NZE; and environmental assessment tools, such as those based on LCA methods, including ATHENA, BEES, LISA, SOFIAS, ENVEST, ECO-quantum, or on the performance of energy systems, such as Energy Plus, TRNSYS, Ecotect and Calener. Another important tool is Level(s), an instrument recently launched by the European Commission (EU), which is currently undergoing testing. It has been developed to be used throughout Europe for the purpose of creating a new EU framework for the sustainability of buildings (Dodd et al., 2017b, 2017a).

An analysis of the literature reveals studies comparing the most widespread, internationally implemented methods. For example, Asdrubali et al. (Asdrubali et al., 2015) compared the LEED and ITACA environmental rating systems by applying both methods to two residential buildings located in Italy; Seinre et al. (Seinre et al., 2014) compared certain indicators and their levels of LEED and BREEAM; Mattoni et al. (Mattoni et al., 2018) carried out a critical review using a methodological approach to evaluate the differences between CASBEE, GREEN STAR, BREEAM, LEED and ITACA, in order to understand which aspects have more influence on the final efficiency rating of each system, and to give users a clearer understanding of the aspects included; Montteroti (Monterotti, 2013) carried out a systematic analysis of the problems of CASBEE, GBTOOL, ITACA and LEED, based on the same common indicators that could serve as a basis for the design of a new tool; Doan et al. (Doan et al., 2017) focussed on BREEAM, LEED, CASBEE and GREEN STAR NZ; Haapio and Viitaniemi (Haapio & Viitaniemi, 2008) carried out a literature review and rough comparison of sixteen methods, including BEES, TEAM, ATHENA, BEAT or ENVEST; and Syahrul et al., (Kamaruzzaman et al., 2016) explored the prominence of different assessment schemes, the ones that were mentioned most frequently in the literature, and the ease of access to assessment manuals, comparing BREEAM, LEED, CASBEE, BEAM, GBLS, HQE, GREEN STAR, VERDE, GBI and MYCREST; while the Department of Environment, Territorial Planning and Housing of the Basque Government classified 34 methods (IHOBE, 2010), and compared BREEAM, LEED, CASBEE, GREEN GLOBES, GREEN STAR and HQE with their own Sustainable Building Guidelines.

The aforementioned studies show that although these methods have a common goal, namely, reduction of environmental impact derived from construction, their analysis reveals important differences in terms of the impacts analysed and their scope of application. Thus, sustainable buildings in different countries are designed and built according to local climatic conditions and the needs of the local population. Furthermore, none of these methods can individually perform a full study over the complete life cycle of a building. Consequently, it is not possible to compare buildings that are sustainable in themselves with other similar buildings that are not. They also show the impossibility of standardization and development of instruments. Furthermore, the methods have been analysed individually, rather than in a group, and no studies have included the most recent Level(s) method. In addition, no study has been found that compares all the most commonly used methods.

For all the above reasons, the objective of this chapter has been the comparative analysis of the current status of sustainable building assessment methods. The study presented here contributes to the existing body of knowledge by highlighting trends and patterns in the field of research into sustainable building assessment methods. This will allow us to, among other things, identify the main similarities and differences between these methods, examine whether they fully assess all aspects of sustainability in each project, and show which stages of the life cycle they cover. In addition, this analysis will include the Level(s) method for the first time, thus giving a complete overview of current trends in building assessment.

2. Materials and methods

For the purposes of this study, a series of specific objectives were developed that shaped the stages of the established working methodology (Figure 11): (i) a quantitative review by means of a review of the literature of current assessment methods and their classification into groups; (ii) a comparative analysis between groups; (iii) a comparative analysis between the methods included in each group; and (iv) a comparative analysis between the traditional methods.

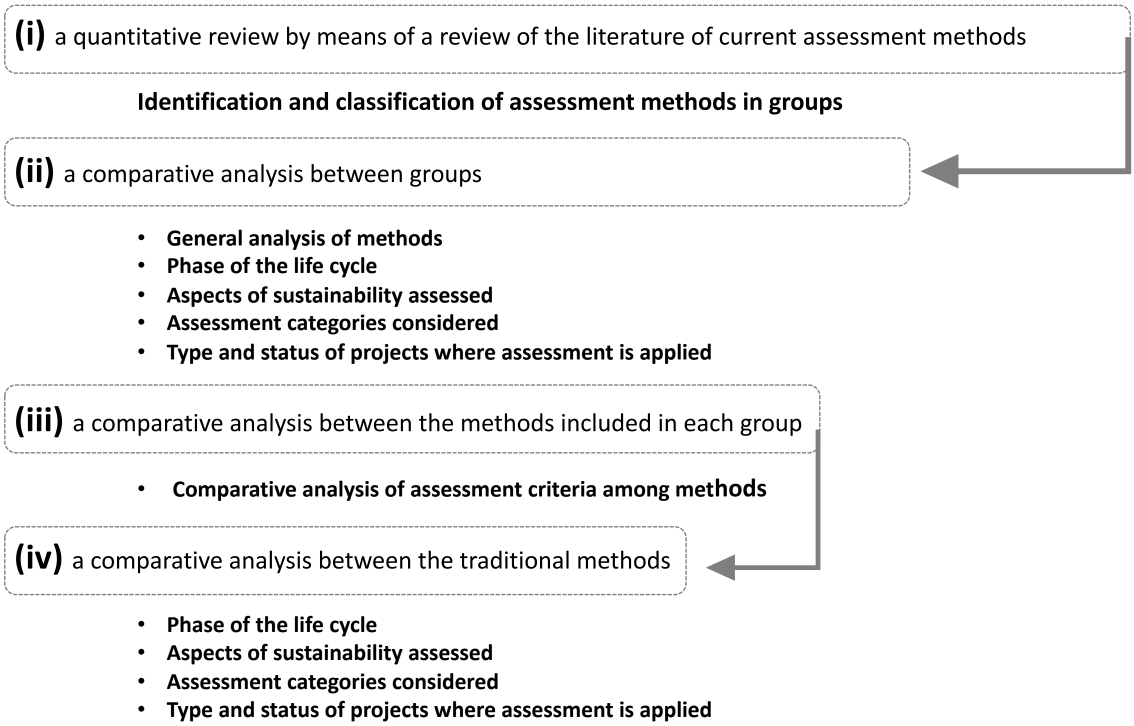


Figure 11. Method.

2.1. Identification and classification of assessment methods in groups

The identification of assessment methods should be based on relevant published documents such as books, journal articles, websites and manuals on sustainability assessment in building. Once identified, different criteria were analysed for their classification. For example, the ATHENA Sustainable Materials Institute introduced the Athena classification, which divides the methods into three levels: (i) tools for comparing products and sources of information; (ii) design of whole buildings and decision-making support tools; and (iii) assessment frameworks or systems for whole buildings (Haapio & Viitaniemi, 2008). The IEA project Annex 31, Energy

Related Environmental Impact of Buildings, classified the methods into five categories: (i) Energy modelling software; (ii) Environmental LCA tools for buildings and building stocks; (iii) Environmental assessment frameworks and rating systems; (iv) Environmental guidelines or checklists for design and management of buildings; and (v) Environmental product declarations, catalogues, reference information, certifications and labels (Haapio & Viitaniemi, 2008).

Finally, in this study, we have considered three groups, which correspond with the classification created by the Public Environmental Management Agency of the Basque Government. This criterion was chosen because it is the most recent system, and takes into account common characteristics, objectives and scope of application (IHOBE, 2010). The system has the following three levels:

(i) Group I: sustainable building assessment systems. These assessment systems (henceforth, Systems) are methods which assess the level of sustainability of a building and its systems or subsystems, as well as classifying and certifying the building based on a series of predefined sustainability parameters or categories (environmental, economic and social) (IHOBE, 2010), which are constantly updated and provide a rating system for sustainable buildings. They are voluntary and educational systems, which are powered by government agencies or developed by non-government organisations. These methods assess a large number of sustainable aspects and types of buildings. Some of them only set out to assess or classify the level of sustainability; others go further and enable the certification of the building by a qualified assessor, who has usually been trained by the agency granting the certification, which is costly. Given that most of the actions that have an impact on a building's use phase are adopted during the design phase, the vast majority of Systems focus on the assessment of new–build constructions and study the entire life cycle of the building. Therefore, they give an understanding of efficient, environmentally–friendly buildings (Awadh, 2017), although in some cases, these Systems may also include urban development projects (Bernardi et al., 2017).

(ii) Group II: sustainable building standards. Sustainable building standards (henceforth, Standards) are methods, also of voluntary application, which call for minimum performance requirements to determine whether a certain building and/or its systems and subsystems comply or fail to comply with requirements (Vega Clemente, 2015). In this case, they do not categorise sustainable buildings, and are usually accepted as being synonymous with good practices. Standards do not cover the complete study of the life cycle of the building, nor do they include urban development projects. Instead, they generally focus on the use phase of the building, particularly energy–related aspects, and leave aside other environmental, social and economic issues. To this end, they establish energy consumption and insulation limits, attempting to minimise energy needs inside buildings and thereby reduce the associated emissions. They usually provide a catalogue of building systems or solutions to enable constructors to comply with these requirements.

(iii) Group III: assessment tools. assessment tools (henceforth, Tools) are not geared towards certification, classification or compliance with minimum requirements, but towards providing the designer with a support tool for the sustainable design of the building and to improve the building's rating when it is assessed using any of the foregoing Systems or Standards. Although there is no need to have an associated Tool, many of the methods included in the groups described above may call for the input of data values that require the use of Tools. These are computer programs designed to support the other methods, and are not always necessary, so they are not able to generate a full assessment. Most of these methods facilitate the selection of building designs, building materials and local service options (energy supply, waste management and transport type) during the design phase (Ali & Al Nsairat, 2009). Two core types of Tools tend to be distinguished: Those based on the LCA which, with greater or lesser scope, place greater emphasis on the environmental impacts of the building than on the environmental aspects in which it operates. Those that assess the energy efficiency of buildings, some of which allow for the energy modelling of buildings.

2.2. Comparative analysis between identified groups

As indicated above, countries around the world have developed many SBAMs, more than 600 in total, along with the rapid development of sustainable buildings (Doan et al., 2017). Due to this high number of SBAMs, the comparative study will be carried out in two phases (Figure 11). In a first phase, the groups identified will be compared based on a series of general characteristics that will include (Figure 11): number of buildings and/or m^2 evaluated, endorsement by the competent authority of the country of application, quality assurance and year of updating. I consider that limiting the methods analysed using these criteria will not compromise the validity of the study and will allow us to select the most representative method within each group. In a second phase, a more complete comparison will be carried out in order to clarify the scope of their application. To this end, the following four variables have been identified and defined (Figure 11):

Phase of the life cycle. The life cycle of a construction project could be defined as the period that spans from the initial planning to the total disposal of the building. The SLR shows the different phases for life cycle analysis as the production of building materials, construction, use and operation, demolition (Kofoworola & Gheewala, 2008), maintenance and disposal (Haapio & Viitaniemi, 2008). For this purposes of this study, a more complete classification was considered, including the aforementioned seven phases, to consider the design phase, since the assessment instruments are more useful during this phase, because they incorporate environmental, social and economic impacts into the design process to minimise impact, and give an insight into and redesign the performance of the building before the start of construction (Ding, 2008).

Aspects of sustainability assessed. Traditionally, SBAMs focused solely on the environmental aspect. However, more recent developments reflect the shift in sustainable building assessment towards the recognition of social and economic aspects (Petrovic-Lazarevic, 2008; Zuo et al., 2012). Consequently, the three indicated aspects were considered for this variable: environmental, social and economic.

Assessment categories considered. The assessment categories are each of the study areas considered by the different methods, in which the various sustainable aspects are addressed. The SLR shows different assessment categories, such as site selection, resources, energy, innovation, indoor environmental quality and materials used, among others (Al-Jebouri et al., 2017; Chandratilake & Dias, 2015; Yu et al., 2015). Based on this review, ten categories were identified to compare and contrast the way in which these are addressed in each Group. The definition and study areas that include these categories are shown in Table 9. Of note is the inclusion of category (C10) Adaptation to Climate Change, since some of the identified methods are currently channelling all their efforts into incorporating new challenges that not only mitigate, but also adapt the building to climate change by minimising its exposure to the potential negative effects of these changes. This means proposing, among many other solutions, stronger constructions designed for extreme temperatures, the construction of coastal infrastructure to mitigate the impact of climatic phenomena, and territorial planning to identify places of high vulnerability, etc., in other words, resilient planning and design actions. Resilience is the ability of a building to adapt to climate change and natural disasters, along with its ability to recover in a timely and efficient manner without incurring damage (Champagne & Aktas, 2016). There is a firm relationship between sustainability and resilience; they complement one another and set out to curb future environmental repercussions through cause and effect, respectively.

Table 9. Categories of assessment considered.

	categories	study areas
C1	Site and sustainable development	impacts related to the planning, design, regeneration and influence of the characteristics of the site; transport management and external light pollution.
C2	Water	performance, cycle, use and monitoring of the various water sources
C3	Materials and resource consumption	use, recycling, reuse and environmental impact of materials and resources
C4	Energy	reduction, control, consumption and use of energy
C5	Indoor environmental quality	environmental ergonomics (reduction and elimination of pollutants, hygrothermal and acoustic comfort, and light quality)
C6	Innovation	designs, processes and strategies that promote sustainability in the built environment and building
C7	Social and economy	use of traditional local materials and techniques, design compatible with cultural values, the cost of use and commercial viability
C8	Service quality	efficiency in the use of the spaces, the capacity of local control of the different systems, and the efficiency of an adequate management and maintenance plan
C9	Circular economy	use of resources and reuse of building materials, systems and subsystems
C10	Adaptation climate change	ability of buildings to adapt to climate change and its consequences without incurring damage

Type and status of projects where assessment is applied. Different authors have included this variable in their studies. For example Illankoon et al. (Illankoon et al., 2017) included new-builds as part of the assessment of the methods; Doan et al. (Doan et al., 2017) also included neighbourhood development manuals; Haapio and Viitaniemi (Haapio & Viitaniemi, 2008) specified that the methods can also be used to assess existing buildings, buildings undergoing refurbishment, and construction products and components. For the purposes of this study, we have considered identifying types of project (building, developments and parts or components of a building) and construction statuses (new–build or existing building) where the identified methods are applied.

2.3. Comparative analysis of assessment criteria among methods

Once the above variables have been identified, at the Group level, the differences between the methods in each category will be analysed. To this end, a set of criteria will be taken into account that are required for a building and/or a project to be sustainable (Illankoon et al., 2017). These must be measurable, mutually independent, and must refer, whenever possible, to qualities or aspects related to the various environmental, economic and social aspects, which may be quantitative or qualitative (Al-Jebouri et al., 2017); they must also be evaluable according to the life cycle phase. Taking into account the criteria requirements, we reviewed the manuals, instructions and guidelines of the different methods used in each of the ten categories considered (Table 9). This enabled us to identify, categorise and standardise the criteria applied to the 35 representative methods of the three groups considered. The set of criteria identified has a critical impact on the study of building performance (Lu et al., 2017) and will influence the decision-making process of decision makers.

3. Results

3.1. Identification and classification of assessment methods in groups.

After a review of the literature, a total of 101 SBAMs were identified and included in Table 10, which gives a general description of the method, including region and country of application, year of launch, organisation in charge, and number of certified buildings.

Of the identified methods, 101 have been classified into the three groups studied (GI, GII and GIII). The last method, Level(s), due to its characteristics, cannot be included in any of the previous groups. It is a new voluntary assessment framework launched by the EU to create a new European Union framework to improve sustainability and steer demand towards better buildings in Europe (Dodd et al., 2017b, 2017a).

Level(s) is the result of widespread research with the industry and the public sector and is a means of designing and building sustainable buildings, based on the main methods of the three previous groups. It provides a set of common indicators and metrics to measure the performance of buildings from all aspects of sustainability throughout their life cycle, introducing the concept of circular economy and adaptation to climate change, shifting away from the linear economic model of 'take, make and waste', and thereby facilitating comparison between sustainable buildings within the EU.

Table 10. Catalogue of methods identificated in this study (part 1).

method	name	year	responsible organisation	BC[1]	reference
GROUP I: SYSTEMS					
Spain					
VERDE	VERDE	2006	Green Building Council España (GBCe)	82	(GBCe, 2006)
Guías de edificación sostenible	Guías de edificación sostenible del País Vasco	2005	IHOBE	N/A	(IHOBE, 2010)
DGNB System	Deutsche Gesellschaft für Nachhaltiges Bauen	2011	AEIC (Associació d'Enginyers Industrials de Catalunya	4	(DGNB, 2011)
BREEAM® ES	Building Research Establishment Environmental Assessment Methodology	2009	Technological Institute of Galicia Foundation (ITG); BRE Global Ltd. (BRE)	375	(BRE Global Ltd, 2009)
Portugal					
Lider A	Leading the Environment for sustainable construction	2005	Instituto Superior Técnico, Lisbon	24	(Portugal, 2005)
SBTool PT	Sustainable Building Tool	2007	iiSBE Portugal, LFTC-UM, ECOCHOICE	N/A	(iiSBE, 2007)
Germany					
DGNB System	Deutsche Gesellschaft für Nachhaltiges Bauen	2007	German Sustainable Building Council (DGNB)	1073	(DGNB, 2011)
BREEAM® DE	Building Research Establishment Environmental Assessment Methodology	2011	TÜV SÜD Industrie Service GmbH (DIFNI) Building Research Establishment (BRE)	245	(BRE Global Ltd, 2009)
United Kingdom					
BREEAM®	Building Research Establishment Environmental Assessment Methodology	1990	Building Research Establishment (BRE)	563731	(BRE Global Ltd, 2009)
CSH	Code for Sustainable Home	2007	Building Research Establishment (BRE) and the Construction Industry Research and Information Association (CIRIA)	N/A	(CSH, 2010)
Austria					
DGNB System	Deutsche Gesellschaft für Nachhaltiges Bauen	2009	Österreichische Gesellschaft für Nachhaltige Immobilienwirtschaft (ÖGNI)	56	(DGNB, 2011)
BREEAM® AT	Building Research Establishment Environmental Assessment Methodology	2010	TÜV SÜD Industrie Service GmbH (DIFNI) Building Research Establishment (BRE)	44	(BRE Global Ltd, 2009)
Luxembourg					
BREEAM® LU	Building Research Establishment Environmental Assessment Methodology	2009	TÜV SÜD Industrie Service GmbH (DIFNI) Building Research Establishment (BRE)	97	(BRE Global Ltd, 2009)

Table 10. Catalogue of methods identificated in this study (part 2).

method	name	year	responsible organisation	BC[1]	reference
GROUP I: SYSTEMS					
Switzerland					
BREEAM® CH	Building Research Establishment Environmental Assessment Methodology	2010	TÜV SÜD Industrie Service GmbH (DIFNI) Building Research Establishment (BRE)	132	(BRE Global Ltd, 2009)
MINERGIE®	The MINERGIE® -Standard for Buildings	1998	Minergie Building Agency	46047	(Minergie Building Agency, 1998)
DGNB System	Deutsche Gesellschaft für Nachhaltiges Bauen	2010	Swiss Sustainable Building Council (SGNI)	3	(DGNB, 2011)
Hungary					
DGNB System	Deutsche Gesellschaft für Nachhaltiges Bauen	2010	TÜV SÜD Industrie Service GmbH (DIFNI)	3	(DGNB, 2011)
France					
HQE™Method	Haute Qualité Environnementale	1996	Association pour la Haute Qualité Environnementale	380000	(HQE-GBC, 1996)
Italy					
Protocollo ITACA	Protocollo ITACA	2004	Istituto per l'Innovazione eTrasparenza degli Appalti e la Compatibilita Ambientale (ITACA)	N/A	(Itaca, 2004)
Czech Republic					
SBTool CZ	Sustainable Building Tool	2010	iiSBE International, CIDEAS	20	(iiSBE, 2010)
Finland					
PromisE	PromisE	2004	Technical Research Centre of Finland (VTT)	N/A	(PromisE, 2004)
Norway					
Økoprofil	Ecoprofil	2004	Byggforsk - Norwegian Building Research Institute	N/A	(Ecoprofil, 2004)
Nordic Countries					
Nordic Swan Ecolabel	Nordic Swan Ecolabel	1989	Nordic Council of Ministers	28	(Nordic Swan Ecolabel, 1989)
Denmark					
DGNB System	Deutsche Gesellschaft für Nachhaltiges Bauen	2012	Green Building Council Denmark	45	(DGNB, 2011)
United States of America					
LEED®	Leadership in Energy and Environmental Design	2000	United States Green Building Council (USGBC)	92000	(LEED US, 2000)
GREEN GLOBES	Green Globes	2004	The Green Building Initiative (GBI)	1352	(GBI, 2000)
Canada					
GREEN GLOBES	Green Globes	2000	The Green Building Initiative (GBI)	149	(GBI, 2000)
BOMA BEST	Building Environmental Standards	2005	BOMA Canada	2227	(BOMA, 2005)

Table 10. Catalogue of methods identificated in this study (part 3).

method	name	year	responsible organisation	BC[1]	reference
GROUP I: SYSTEMS					
Mexico					
LEED® MEXICO	Leadership in Energy and Environmental Design	2008	Mexico GBC	N/A	(GBCI México, 2008)
Chile					
CES®	Sustainable Building Certification	2014	Chile Green Building Council (Chile GBC)	13	(Chile GBC, 2010)
LEED® Chile	Leadership in Energy and Environmental Design	2010	Chile Green Building Council (Chile GBC)	321	(Chile GBC, 2010)
Argentina					
LEED® Argentina	Leadership in Energy and Environmental Design	2007	Argentina Green Building Council (AGBC)	112	(AGBC, 2007)
Brazil					
LEED® Brazil	Leadership in Energy and Environmental Design	2007	Bazil Green Building Council (Brazil GBC)	714	(LEED Brasil, 2007)
AQUA-HQE	Haute Qualité Environnementale	2008	Fundação Vanzolini	N/A	(AQUA-HQE, 2008)
South Africa					
GREEN STAR SA	Green Star South Africa	2008	Green Building Council SA (GBCSA)	313	(GBCSA, 2008)
SBAT	South African Sustainable Building Assessment Tool	2002	Council for Scientific and Industrial Research (CSIR)	N/A	(SBAT, 2002)
Australia					
GREEN STAR	Green Star Australia	2003	Green Building Council Australia (GBCA)	1,715	(Green Star, 2003)
NABERS™	National Australian Built Environment Ratings	2008	NSW (New South Whales Government)	2,736	(NABERS, 2008)
New Zealand					
GREEN STAR NZ	Green Star New Zealand	2007	New Zealand GBC	151	(GREEN STAR NZ, 2007)
Qatar					
GSAS	Global Sustainability Assessment System	2009	The Gulf Organisation for Research and Development (GORD)	N/A	(GSAS, 2009)
Indian					
LEED® India	Leadership in Energy and Environmental Design	2011	Indian Green Building Council (IGBC)	630	(LEED India, 2011)
TERI-GRIHA	Green Rating for Integrated Habitat Assessment	2007	The Energy & Research Institute (TERI)	1200	(TERI-GRIHA, 2007)
United Arab Emirates					
Estidama	Pearl Rating System	2010	Abu Dhabi Urban Planning Council (UPC)	N/A	(Awadh, 2017)
Malaysia					
MYCREST	Malaysian Carbon Reduction and Environmental Sustainability Tool	2013	Public Work Department Malaysia	N/A	(MyCrest, 2013)

Table 10. Catalogue of methods identificated in this study (part 4).

method	name	year	responsible organisation	BC[1]	reference
GROUP I: SYSTEMS					
Malasya					
GBI	Green Building Index	2010	Malaysian Institute of Architects and the Association of Consulting Engineers Malaysia	412	(GBI, 2010)
Hong Kong					
CEPAS	Comprehensive Environmental Performance Assessment Scheme for Buildings	2002	HK Building Department	N/A	(CEPAS, 2002)
HK BEAM PLUS	Building Environmental Assessment Method	1996	Green Building Council Limited de Hong Kong (HKGBC)	467	(HKGBC, 1996)
Taiwan					
EEWH	EEWH Evaluation Manual	1999	Architecture and Building Research Institute	4300	(EEWH, 1999)
China					
GOBAS	Green Olympic Building Assessment System	2003	Minister of Science & Technology	N/A	(Zhang et al., 2017)
ESGB	Evaluation Standard for Green Building	2006	Ministry of Housing and Urban-Rural Development (MOHURD)	1440	(Zhang et al., 2017)
GBL	Green Building Labelling	2008	Ministry of Housing and Urban-Rural Development (MOHURD)	N/A	(Ye et al., 2013)
GHEM	Green Housing Evaluation Manual	2002	China Real Estate Chamber of Commerce	N/A	(Bernardi et al., 2017)
Japan					
CASBEE	Comprehensive Assessment System for Built	2001	Japan Sustainable Building Consortium (JSBC)	330	(CASBEE, 2001)
South Korea					
G-SEED	Green Standard for Energy and Environmental Design	2002	Ministry of Land, Infrastructure, & Transport (MOLIT)	1723	(G-SEED, 2002)
Singapore					
GREEN MARK	GREEN MARK	2005	BCA (Building and Construction Authority)	3000	(GREEN MARK, 2005)
Vietnam					
LOTUS	LOTUS	2007	Vietnam Green Building Council (VGBC)	72	(LOTUS, 2007)
Egypt					
GPRS	Green Pyramid Rating System	2011	The Egyptian Green Building Council	N/A	(GPRS, 2011)
Global					
WELL	WELL Building Standard	2014	The International WELL Building Institute (IWBI); World GBC	834	(WELL, 2014)

Table 10. Catalogue of methods identificated in this study (part 5).

method	name	year	responsible organisation	BC[1]	reference
GROUP II: STANDARS					
Global					
LEB	Low-energy buildings	1994	N/A	N/A	(LEB, 1994)
Germany					
PASSIVHAUS	Passivhaus standard	1990	The International Passive House Association	4299	(Passivhaus, 1990)
United Kingdom					
ZCB	Zero Carbon Buildings	1994	N/A	N/A	(Hui, 2015)
United States of America					
nZEB	Net Zero Energy Building	2000	International Living Future Institute	N/A	(NZEB, 2000)
NGBS	National Green Building Standard	2008	National Association of Home Builders (NAHB)	137383	(NGBS, 2008)
Mexico					
CEV	Housing Building Code	2007	National Housing Commission (CONAVI)	N/A	(CEV, 2007)
Canada					
BUILT GREEN®	BUILT GREEN	2001	BUILT GREEN	30290	(Built Green, 2001)
GROUP III: TOOLS					
Canada					
ATHENA™	Athena Impact Estimator for Buildings	2002	ATHENA Sustainable Material Institute	N/A	(ATHENA, 2002)
United States of America					
BEES 4.0	Building for Environmental and Economic Sustainability	1998	NIST (National Institute of Standards and Technology)	N/A	(BEES, 1998)
Holland					
ECO-quantum	ECO-quantum	1999	Sustainability research and consultancy department of the University of Amsterdam (IVAM)	N/A	(Kumanayake & Luo, 2018)
United Kingdom					
ENVEST II	ENVEST II	2003	Building Research Establishment	N/A	(Haapio & Viitaniemi, 2008)
CCaLC Tool	Carbon footprinting tool	2007	University of Manchester	N/A	(Tool, 2007)
France					
ELODIE	ELODIE	2006	CSTB's Environment division	N/A	(Berardi, 2015)
TEAM™	TEAM™	1995	Ecobilan	N/A	(Haapio & Viitaniemi, 2008)
EQUER	EQUER	1995	Ècole des Mines de Paris	N/A	(Haapio & Viitaniemi, 2008)
ESCALE	ESCALE	2000	CTSB and the University of Savoie	N/A	(Haapio & Viitaniemi, 2008)

Table 10. Catalogue of methods identificated in this study (part 6).

method	name	year	responsible organisation	BC[1]	reference
GROUP III: TOOLS					
France					
PAPOOSE	PAPOOSE	1997	TRIBU Architects	N/A	(Haapio & Viitaniemi, 2008)
Denmark					
BEAT 2002	BEAT 2002	2000	Danish Building Research Institute (SBI)	N/A	(Haapio & Viitaniemi, 2008)
Germany					
GABI	GABI	1999	IKP University of Stuttgart, PE Product Engineering GmbH	N/A	(Haapio & Viitaniemi, 2008)
GEMIS	Global Emission Model of Integrated Systems	1990	Oeko-Institut (Institute for applied Ecology)	N/A	(GEMIS, 1990)
LEGEP®	LEGEP®	2001	LEGEP Software GmbH	N/A	(Haapio & Viitaniemi, 2008)
OpenLCA	OpenLCA	2013	GreenDeltaTC GmbH	N/A	(OpenLCA, 2013)
Umberto	Umberto	1994	Ifu Hamburg GmbH	N/A	(UMBERTO, 1994)
Netherlands					
SIMAPRO	SIMAPRO	1990	Pre-Consultants	N/A	(SimaPro, 2004)
Italy					
eVerdEE	eVerdEE	2004	ENEA	N/A	(Berardi, 2015)
Switzerland					
Eco-Bat	Eco-Bat	2008	University of Applied Science of Western Switzerland	N/A	(Eco-Bat, 2008)
Sweden					
Miljöstatus	Environmental Status Model	1997	Association of the Environmental Status of Buildings	N/A	(Miljöstatus, 1997)
EcoEffect	EcoEffect	2006	Royal Institute of Technology	N/A	(Haapio & Viitaniemi, 2008)
Finland					
BeCosT	BeCosT	2003	Technical Research Centre of Finland (VTT)	N/A	(Kim et al., 2017)
Japan					
AIST-LCA	AIST-LCA	1996	National Institute for Resource and Environment	N/A	(AIST-LCA, 1996)
AIJ-LCA	AIJ-LCA	2003	Japan Architectural Society	N/A	(Kumanayake & Luo, 2018)
Carbon Navigator	Carbon Navigator	2009	Daisei construction	N/A	(Kumanayake & Luo, 2018)
GEM-21P	GEM-21P	2008	Shimizu Corporation	N/A	(Kumanayake & Luo, 2018)
Korea					
SUSB-LCA	SUSB-LCA	2007	Sustainable Building Research Center, Hanyang University	N/A	(K. Lee et al., 2009)
K-LCA	K-LCA	2004	Korea Institute of Construction Technology	N/A	(Baek et al., 2013)
BEGAS	BEGAS	2013	Sustainable Building Research Center	N/A	(Roh et al., 2014)

Table 10. Catalogue of methods identificated in this study (part 7).

method	name	year	responsible organisation	BC[1]	reference
GROUP III: TOOLS					
Australia					
LISA	LCA In Sustainable Architecture	2003	BPH- Australia and Universidad de Newcastle y el Swedish Building Institute)	N/A	(LISA, 2003)
United States of America					
Energy Plus	Energy Plus	1998	U.S. Department of Energy (DOE)	N/A	(EnergyPlus, 1998)
TRNSYS	Transient System Simulation Tool	1975	University of Wisconsi	N/A	(TRNSYS, 1975)
United Kingdom					
Design Builder	Design Builder	N/A	DesignBuilder Software Ltd	N/A	(Design Builder, n.d.)
Global					
Ecotect	Ecotect	2005	Autodesk	N/A	(L. Yang et al., 2014)
Spain					
HULC	Herramienta Unificada LIDER-CALENER	2015	Ministerio de Industria, Turismo y Comercio de España	N/A	(HULC, 2015)
LEVEL(S)					
European Union					
LEVEL(S)	Building sustainability performance	2017	European Commission	N/A	(Dodd et al., 2017b, 2017a)

Level(s) objectives are: (i) sensitise the general public, developers and public procurement services about the need to have better buildings and increase the demand for them; (ii) increase knowledge about the efficient use of resources in the built environment in order to foster better decision-making processes by designers, architects, developers, construction companies, manufacturers of construction products, investors and real estate owners; and (iii) provide a common approach in the EU to assess the sustainability of buildings and the built environment. The flexible indicator can also be incorporated into new and existing assessment systems.

Figure 12 provides an overview of the macro-objectives, indicators and scenarios that are part of Level(s). There are six in total, laying down objectives in terms of environment, health and wellbeing, cost, value and risk. Based on these objectives, a series of indicators derived from existing instruments and standards were developed (Dodd et al., 2017b, 2017a), while the framework is compatible with the use of three levels of performance assessment that may be carried out using these indicators.

- The first level, the assessment of common performance, provides common units of measurement and basic calculation instruments that can be used directly by professionals or easily adopted by the creation of assessment systems, information tools for investors and the public sector.
- The second level, the assessment of comparative performance, is aimed at professionals who wish to make significant comparisons between functionally equivalent buildings.
- The third level, the assessment of optimised performance, provides the most advanced use of each indicator, including more precise calculations and modelling of the design and performance, in order to anticipate future costs, risks and opportunities throughout the life cycle. In some cases, the framework also allows for the use of calculation methods from existing methods.

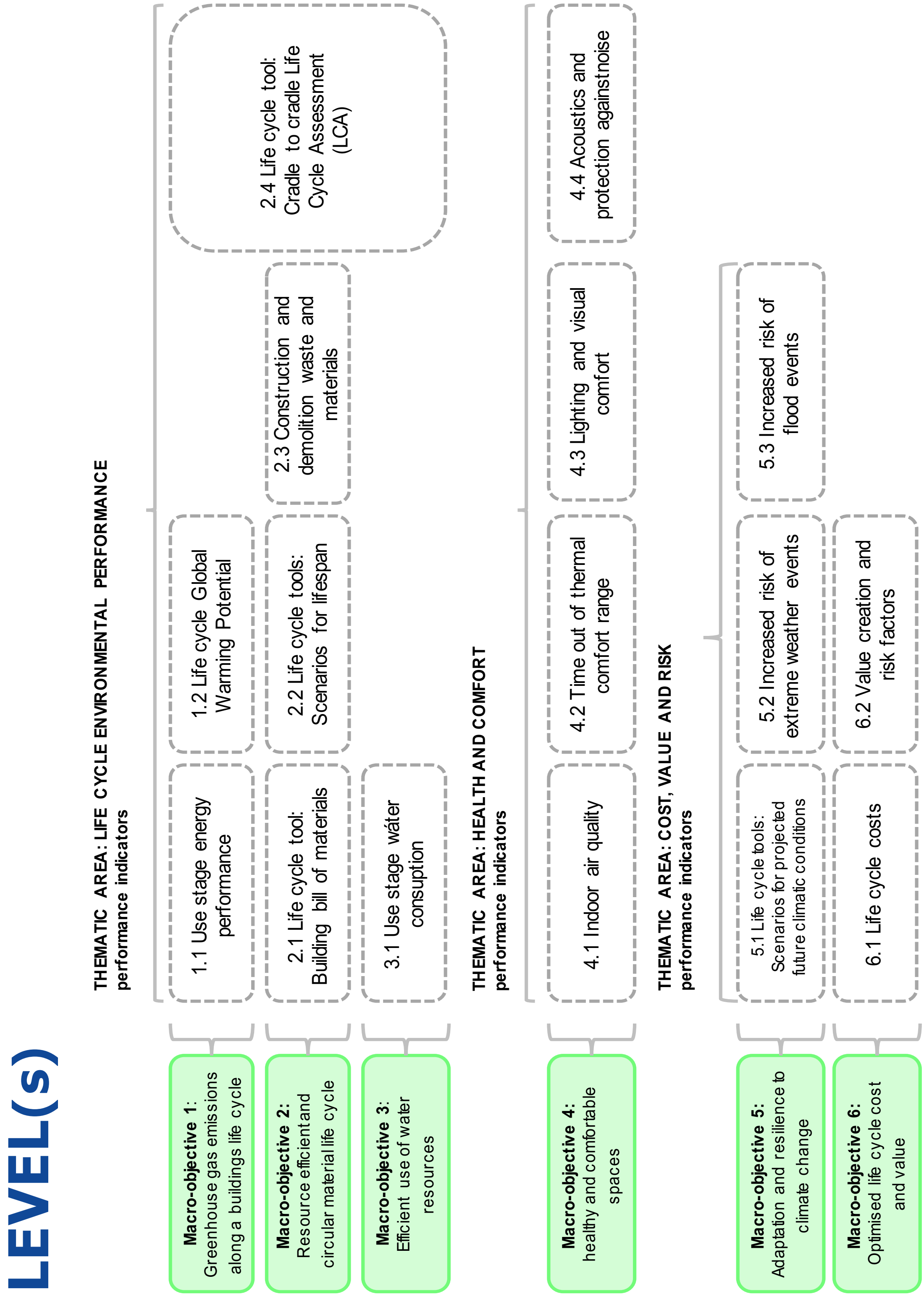


Figure 12. Overview of the Level(s) framework.

Given the importance that Level(s) will have in Europe, it has been included in this study as a single method (Figure 13), which will allow comparison with other methods.

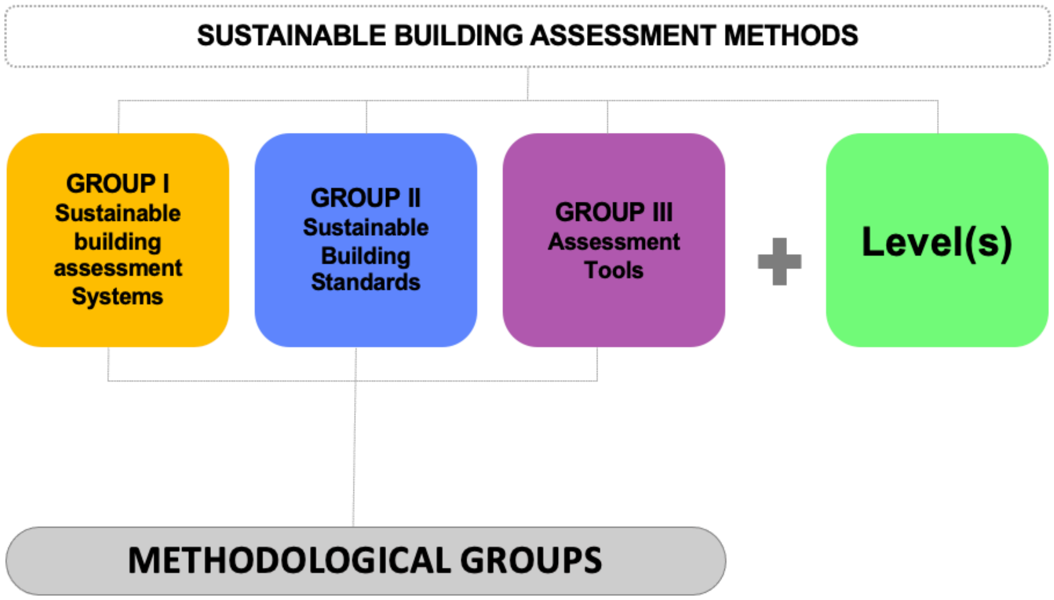


Figure 13. Classification of SBAMs.

3.2. Comparative analysis of methodological groups

3.2.1. General analysis of methods

In the first phase, we will analyse the general characteristics of the methods included in this study. To do this, we will compare their evolution over time in terms of their development and area of application.

An analysis of the timeline of sustainable building assessment methods, included in Table 7, shows an uneven trend, in terms of both the timeline and the group to which they belong, as shown in Figure 14. The analysis shows three key moments in the evolution of the methods: from the implementation of the first instrument up to the early 1990s, when few methods had been developed, due in part to the lack of knowledge about the concept of sustainable building; the introduction in 1990 of the BREEAM, and the advent of methods that took into account the social and economic aspect of construction, in contrast to earlier methods that only considered its environmental effects; and 2000, coinciding with the expanded scope of application of the famous LEED system (LEED US, 2000), when a large number of methods began to appear.

This marked increase can be attributed to the growing recognition of sustainable buildings among industries and construction authorities around the world, as well as to the positive reception and manifestation of the three pioneering methods. Finally, Level(s), the most recent method, currently in a trial period, could mark a turning point in the evolution of methods (Dodd et al., 2017b, 2017a). If we observe evolution from the point of view of the groups (Figure 14), it can be seen that Systems, followed by Tools, are the most widely developed methods, especially since 2000; in contrast, the number of Standards has remained more or less steady. Despite a relatively brief history, the creation of environmental assessment methods has attracted the attention and interest of academia (Haapio, 2012); and regardless of the date of their initial launch, most of the methods have evolved over time, incorporating the latest technologies, regulations and practical experience (Yu et al., 2015).

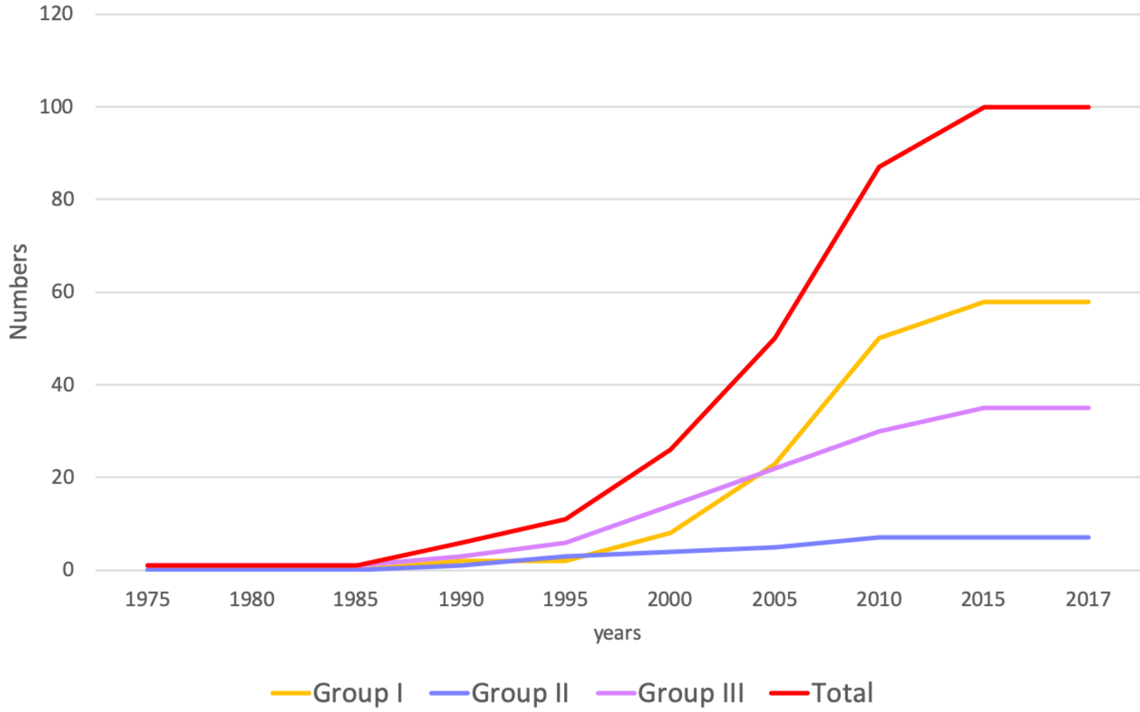


Figure 14. Evolution of the number of sustainable building assessment methods.

Analysing the organizations responsible for the development of the methods, Table 10 shows they have been developed by various non-governmental organisations (NGOs), research institutes, universities, private companies, etc., with 70% of the Systems developed and administered by GBC, which are independent non-profit structures made up of companies and organisations in more than 70 countries that are members of the global network of the World Green Building Council (WGBC), which was set up to coordinate the efforts of GBC around the world. In the case of Tools and Standards, most have been developed by research institutes, universities or private companies.

On analysing the scope of application of the groups, Figure 15 shows that Systems are the most widespread on a global level, with a strong presence in Europe, North America, South America and Asia. They are followed by Tools, with a similar scope, except in Asia. Standards is the least widespread group, being located in North America and Europe. Finally, Level(s) only covers Europe. It can be seen that assessment methods are scarce among less economically developed countries, such as in Africa and Asia, indicating that the higher cost of constructing sustainable buildings has become a major obstacle to encouraging these countries to construct sustainable buildings. The main problem, as Jha et al. (Vyas & Jha, 2018) point out, is that energy saving, indoor air quality and other sustainability factors are not taken into account during the design phase, and only become evident once the building is in use.

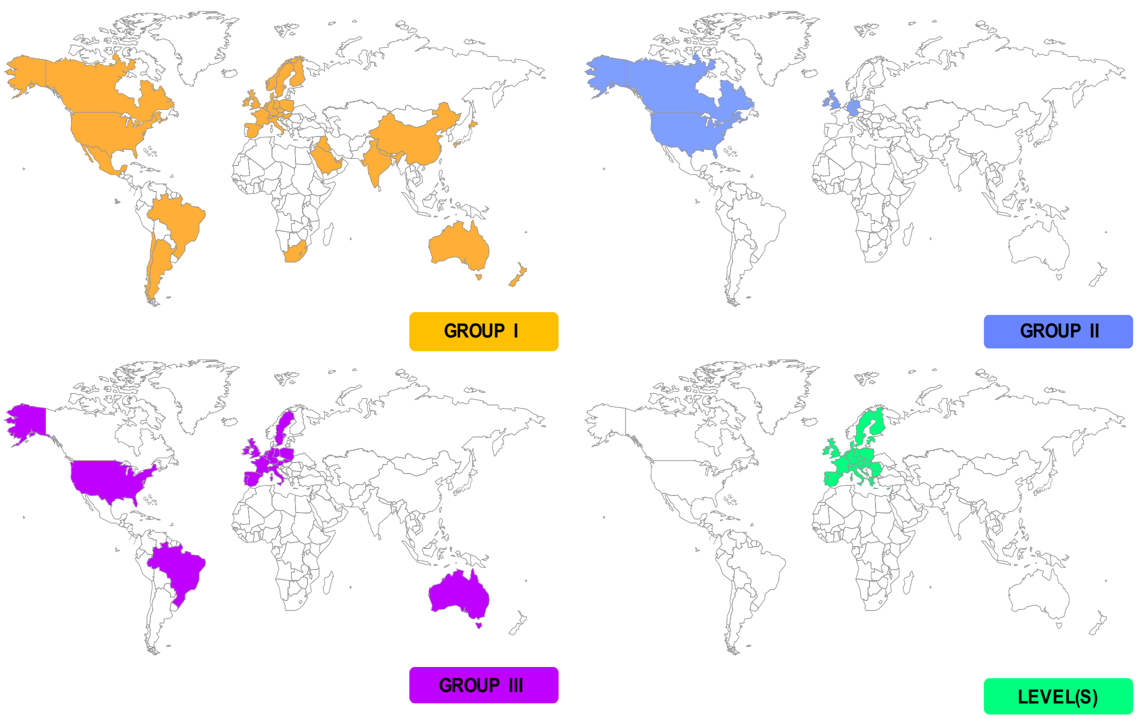


Figure 15. Area of application of the methods.

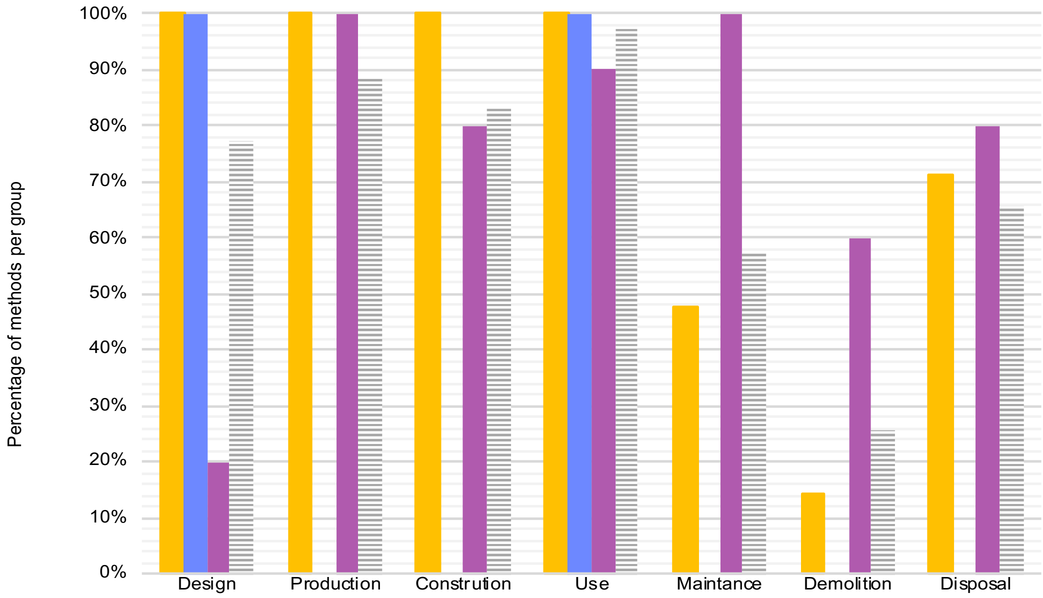
3.2.2. Comparative analysis between groups

Given the number of methods identified (Table 10), the most representative ones from groups I, II and III were selected according to the number of buildings and/or m^2 assessed, endorsement from the competent authority of the country of application, quality assurance background, and year of update. We consider that eliminating methods based on these criteria will not compromise the validity of the study. As a result, 35 methods were selected; of these, 21 are Systems, 4 are Standards and 10 are Tools.

In order to compare groups, I, II and III, their main characteristics were analysed using the four variables identified and defined in the previous section: (i) phase of the life cycle for application; (ii) aspects of sustainability assessed; (iii) categories considered; (iv) type and project status where assessment is applied. In this study, Level(s) was included as a single instrument, not in a group, and therefore has not been included in this comparative phase.

3.2.2.1. Phase of the life cycle in which assessment is applied

The number of phases considered in the methods analysed is very varied. It can be observed in Figure 16 that regardless of the group to which they belong, the phase of use is included in most (97%) of the methods analysed; in contrast, the demolition phase is only present in 26% of the methods.



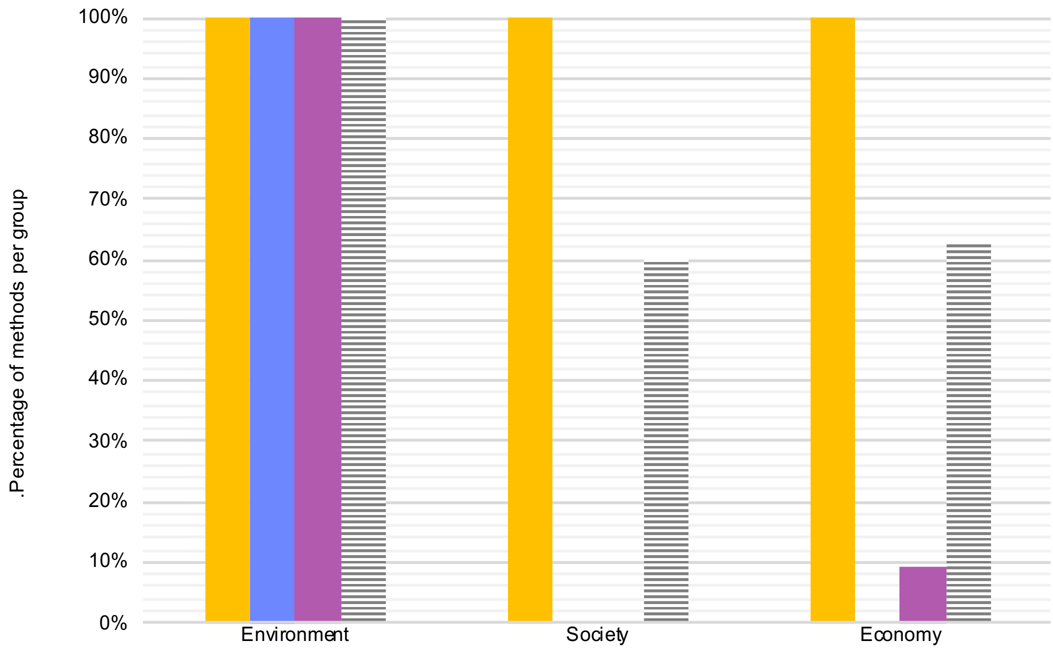
	Design	Production	Construtıon	Use	Maintance	Demolition	Disposal
Group I (Systems)	100%	100%	100%	100%	48%	14%	71%
Group II (Standars)	100%	0%	0%	100%	0%	0%	0%
Group III (Tools)	20%	100%	80%	90%	100%	60%	80%
Average	77%	89%	83%	97%	57%	26%	66%

Figure 16. Percentage of methods per group, which include the phases of the life cycle.

Analysing the data according to Group (Figure 16), the number of phases consideration differs. The methods in Group I (Systems) consider the greater number of phases, so all of them include the phases of design, production, construction and use, while the phases of disposal, maintenance and demolition are considered in 71%, 48% and 14% of them, respectively. By contrast, Group II (Standards) only considers two phases (design and use), both of which are present in all the methods included in this group. Finally, all the methods of Group III (Tools) include the phase of production and maintenance, 90% of them include the phase of use, 80% include construction and disposal, 60% include demolition, and only 20% include design.

3.2.2.2. Sustainable aspects considered

Figure 17 shows the percentage of methods, regardless of the group to which they belong, that take into account the three aspects of sustainability: environmental, social and economic. From the point of view of sustainable aspects, it can be observed that the environmental aspect is present in all methods, to a greater or lesser extent, followed by the economic aspect, closely followed by the social aspect. It is important to point out that even if a method considers different aspects (environmental, social or economic) this does not mean that it includes all the parameters required by an unquestionably sustainable building.



	Environment	Society	Economy
Group I (Systems)	100%	100%	100%
Group II (Standars)	100%	0%	0%
Group III (Tools)	100%	0%	9%
Average	100%	60%	63%

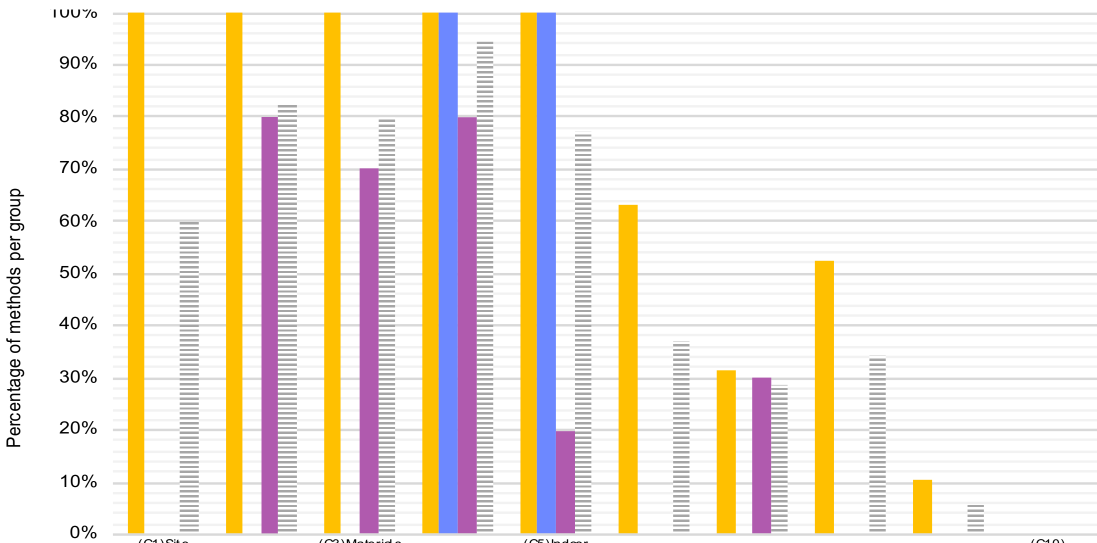
Figure 17. Percentage of the three aspects of sustainability

Analysing the data according to Group, the number of aspects considered also differs. The methods included in Group I (Systems) are the only ones to consider all three aspects. In contrast, Group II (Standards) only considers the environmental aspect. In the case of Group III (Tools), all the methods consider the environmental aspect, none consider the social aspect, and only 9% consider the economic aspect.

3.2.2.3. Assessment categories

As in the case of the variables above, the number of categories considered in the analysed methods varies greatly. Figure 18 shows that regardless of the group to which it belongs, none of the categories are present in all the methods, with (C4) Energy being present in 94%, whereas (C9) Circular Economy is only considered in 6%. Finally, it can be observed that the criterion (C10) Adaptation to Climate Change is not considered in any of the methods, as commented previously, because even though developers are updating the different versions, it has not so far been included.

Analysing the data according to Group, the number of categories considered also differs, as occurs in the variables analysed above; thus, all the methods included in Group I (Systems) cover the categories (C1) Site and Sustainable Development, (C2) Water, (C3) Materials and Resources, (C4) Energy and (C5) Indoor Environmental Quality, whereas categories (C6) Innovation, (C7) Social and Economic, (C8) Quality of Service and (C9) Circular Economy are present in 63%, 53%, 32% and 11% of the Systems, respectively. At the opposite extreme is Group II (Standards), which only considers categories (C4) Energy and (C5) Indoor Environmental Quality, albeit in all the methods included. Finally, in the case of Group III (Tools), it can be observed that only five of the ten categories are considered, with (C2) Water and (C4) Energy being the most ubiquitous, in 80% of cases, followed by (C3) Materials and Resources, whereas only 30% and 20% of the methods of this group cover (C7) Social and Economic and (C5) Indoor Environmental Quality, respectively.

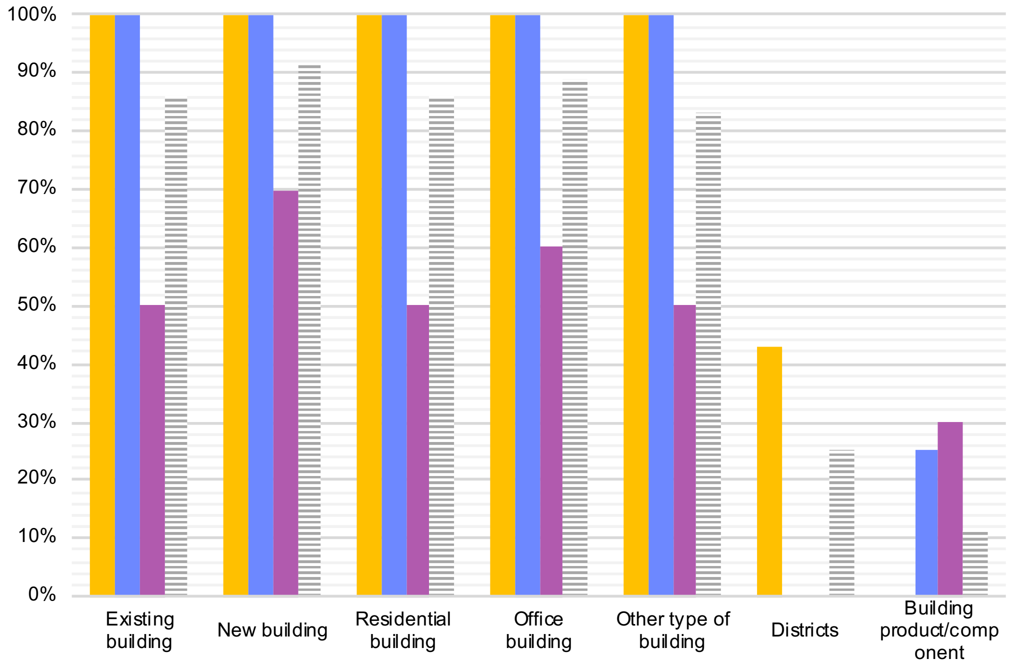


	(C1) Site suitability development	(C2) Water	(C3) Materials and Resource Consumption	(C4) Energy	(C5) Indoor Environmental Quality	(C6) Innovation	(C7) Social and Economy	(C8) Service Quality	(C9) Circular Economy	(C10) Adaptation climate change
Group I (Systems)	100%	100%	100%	100%	100%	63%	32%	53%	11%	0%
Group II (Standars)	0%	0%	0%	100%	100%	0%	0%	0%	0%	0%
Group III (Tools)	0%	80%	70%	80%	20%	0%	30%	0%	0%	0%
Average	60%	83%	80%	94%	77%	37%	29%	34%	6%	0%

Figure 18. Percentage of assessment categories.

3.2.2.4. Type and status of projects where assessment is applied

Analysing the data from the perspective of the type and status of projects where assessment is applied, it can be observed in Figure 19 that none are present in all the methods, regardless of the group to which they belong. New−builds are the most widely considered, in 92% of the identified methods, whereas only 11% of methods assess components or parts of a building.



	Existing building	New building	Residential building	Office building	Other type of building	Districts	Building product/component
Group I (Systems)	100%	100%	100%	100%	100%	43%	0%
Group II (Standars)	100%	100%	100%	100%	100%	0%	25%
Group III (Tools)	50%	70%	50%	60%	50%	0%	30%
Average	86%	92%	86%	89%	83%	25%	11%

Figure 19. Percentage of type and status of projects.

Depending on the method-related group, the level of consideration of the type and status of projects also differs, as indicated in Figure 19. All methods in Group I (Systems) are applied to both existing buildings and new-builds, whether private residences, blocks of flats, office buildings and other buildings, while only 43% of the systems assess neighbourhoods. In contrast, none of the methods in this group cover components or parts of a building.

In the case of Group II (Standards), we can see that none of the methods in this group consider neighbourhoods, and only one of them covers components or parts of a building, while all of them assess existing buildings and new-builds, whether residential, office buildings or other types of buildings. None of the methods identified in Group III (Tools) cover neighbourhoods, as in the case of Standards, while 70% of them assess new-builds, and only 30% of Tools consider components or parts of a building.

3.3. Comparative analysis of assessment criteria among methods

In the foregoing section, we drew attention to the differences between Groups I, II and III. However, methods also differ within the same group, so a detailed analysis will be carried out below. In each category considered, an analysis was made of the included criteria, making it possible to compare the methods in each group. A comparative analysis of Level(s) with traditional methods has been included, because its characteristics cannot be included in any of the previous groups.

3.3.1. Comparative analysis of groups

Taking into account the criteria requirements, and based on the established methodology, 150 criteria were identified for the ten categories considered and summarized in Figure 20. Given the sheer scale of the results obtained from this analysis, in this study we have only analysed the 32 criteria belonging to category (C1) Site and Sustainable Development in Group I (Systems) (Table 11). This process was applied to all the criteria, categories and groups, giving the results shown in Figures 21 and 22, and discussed below.

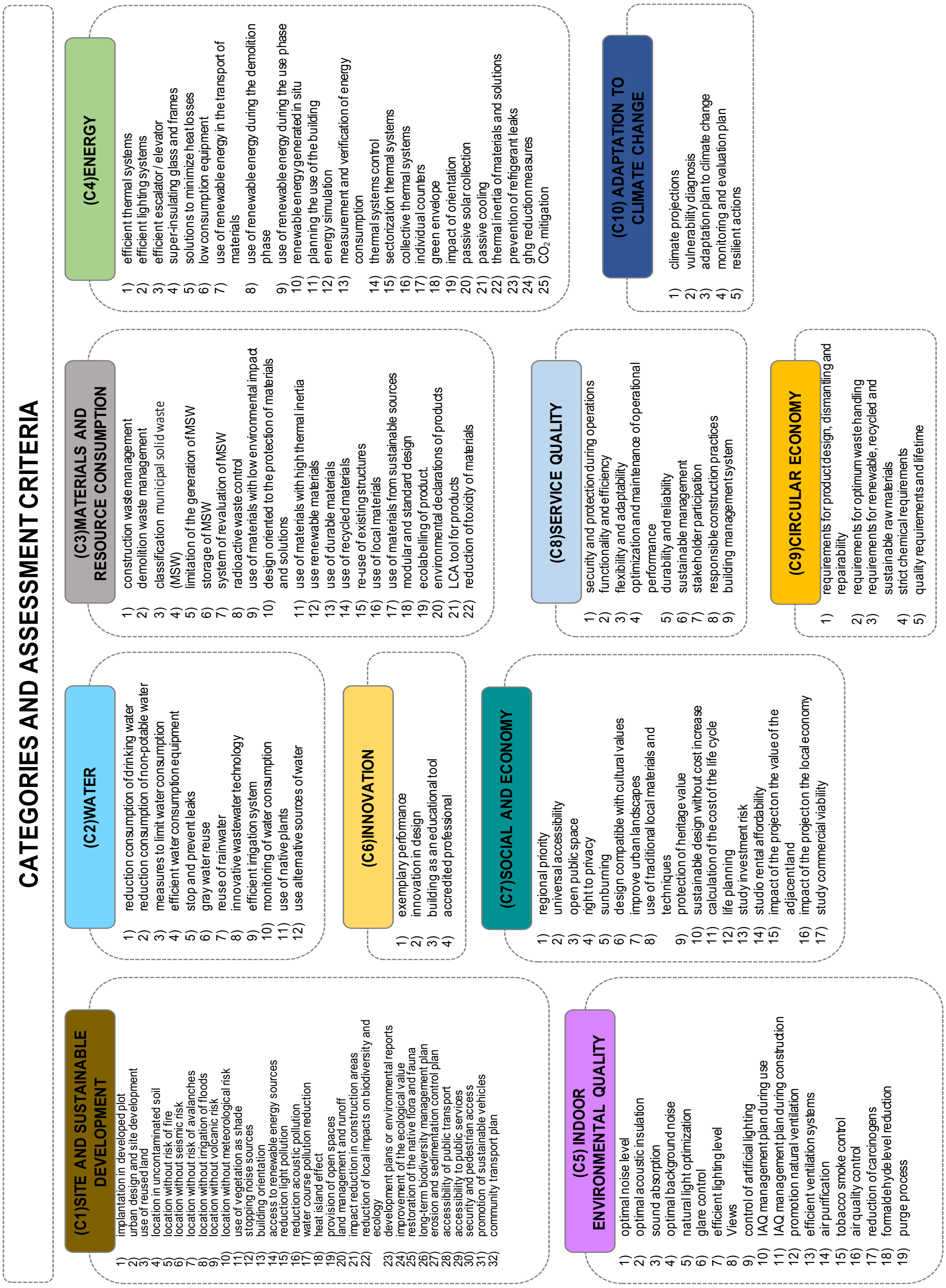


Figure 20. Categories and assessment criteria

Table 11. Relationship of each System with the 32 criteria belonging to category (C1).

GROUP I (SYSTEMS)

CRITERIA	VERDE	BREEAM	HQE	ITACA	IHOBE	Estidama	NABERS	SBAT	DGNB	LEED	CASBEE	Green Star	BEAM PLUS	GREEN GLOBES	SB TOOL	GREEN MARK	BOMA BEST	GBI	AQUA	ESGB	GSAS
1		■	■	■	■	■		■	■	■	■	■	■	■	■	■	■		■	■	■
2			■	■	■	■	■	■	■	■	■	■	■	■	■		■			■	■
3		■	■		■	■	■	■	■	■	■	■	■			■	■	■	■	■	■
4		■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■		■
5		■						■	■	■			■	■	■						
6		■							■	■											
7		■						■	■	■											
8		■	■					■	■	■					■			■	■		
9		■																			
10		■		■				■	■	■											
11	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
12			■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■
13			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
14								■	■	■	■	■	■	■	■	■	■	■	■	■	■
15	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	
16	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■				■
17		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	
18	■		■		■	■	■	■	■			■	■	■	■			■		■	■
19	■	■	■				■	■		■	■	■	■		■	■	■	■	■	■	■
20	■	■		■	■		■	■	■	■	■	■	■	■	■		■	■		■	■
21		■				■	■		■	■		■	■	■	■	■					
22	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
23				■								■		■	■	■					
24	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■
25	■		■	■	■	■	■	■	■			■	■	■	■	■	■	■	■	■	■
26		■	■									■		■		■			■		■
27	■	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■	■	■	■
28	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
29	■	■		■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■
30	■	■		■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■
31	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
32			■		■	■					■	■	■		■				■		
	42%	70%	61%	55%	58%	61%	61%	81%	82%	79%	64%	79%	76%	61%	79%	64%	64%	55%	64%	61%	63%

3.3.1.1. Group I: Systems.

As explained above, by way of example, Table 11 includes the relationship of each system with the 32 criteria belonging to category (C1) Site and Sustainable Development. In this table, it can be seen that none of the Systems include all the criteria of the category considered, although all of them consider more than half, except for Verde, which only considers 42%. DGNB is the System which considers the most criteria, 82% in total. Specifically, the criteria which are present in all the methods are: "use of vegetation as shade" and "accessibility to public transport", while the criterion "location without volcanic risk" is only considered in BREEAM.

This analysis was repeated for the remaining ten categories in order to obtain the total percentage of criteria included in the methods in Group I (Systems), giving the results shown in Figure 21. It can be observed that the average percentage of criteria present in the methods of this group is 62%, with a maximum of 69% in LEED and a minimum of 41% in VERDE. However, it was observed that all these Systems include criteria related to thermal and acoustic comfort; to the quality of lighting and air; to water usage, quality, efficiency and savings; to the reduction of energy consumption, and to the monitoring and use of energy–efficient systems. This is explained by the fact that these methods have been designed, in part, to adapt sustainable buildings to the wellbeing of the end user.

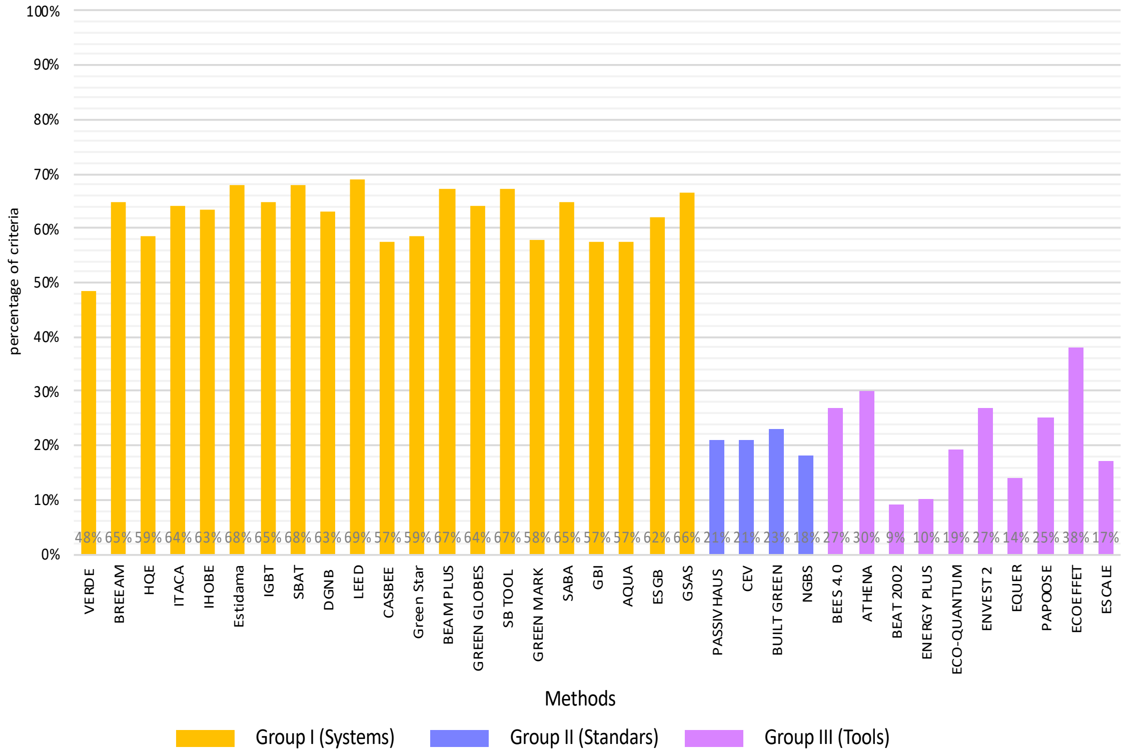
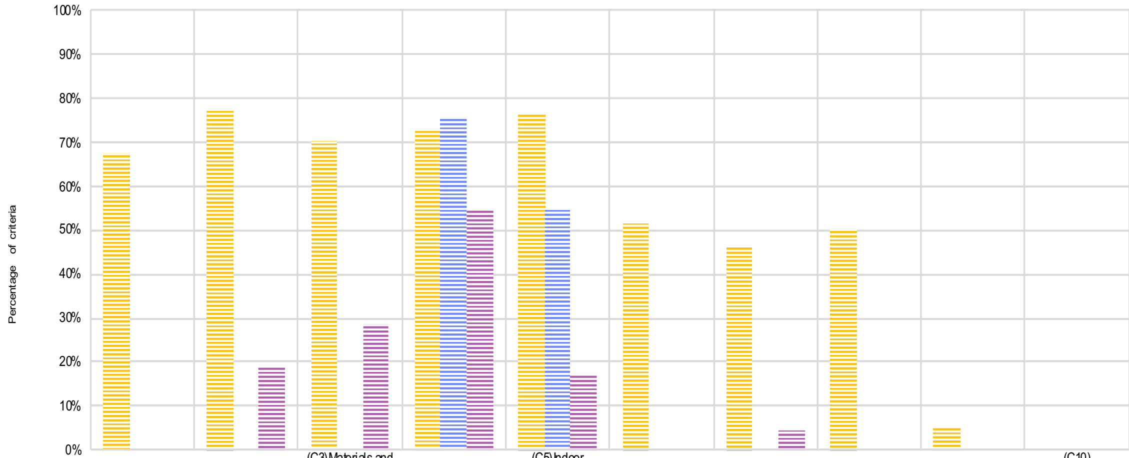


Figure 21. Percentage of criteria achieved by the methods.

On analysing the presence of criteria for each of the categories (Figure 22), it was observed that those corresponding to categories included in the most recent sustainable building concepts, such as (C9) Circular Economy, are, at 5%, the least prevalent. In the remaining cases, they range from 46% in category (C7), Social and Economic, and 77% in categories (C2), Water, and (C5), Indoor Environmental Quality. Once again, it is clear that the social and economic aspects are the least developed, as these have only recently have been included in sustainability and are the most difficult to assess.



	(C1) Site suitability development	(C2) Water	(C3) Materials and Resource Consumption	(C4) Energy	(C5) Indoor Environmental Quality	(C6) Innovation	(C7) Social and Economy	(C8) Service Quality	(C9) Circular Economy	(C10) Adaptation climate change
Group I (Systems)	67%	77%	70%	73%	77%	51%	46%	50%	5%	0%
Group II (Standars)	0%	0%	0%	76%	55%	0%	0%	0%	0%	0%
Group III (Tools)	0%	19%	29%	55%	17%	0%	4%	0%	0%	0%

Figure 22. Percentage of criteria per Categories.

3.3.1.2. Group II. Standards

From the point of view of the methods in this group, Figure 21 shows that none of the analysed Standards contain all the criteria. The presence of criteria in all the Standards hovers around 20%. From the point of view of the criteria, analysed by categories, as can be seen in Figure 22 that Standards only considers two categories, (C4) Energy and (C5) Indoor Environmental Quality, with 76% and 55% respectively, which underlines the greater concern of Standards for energy efficiency, as opposed to user wellbeing.

3.3.1.3. Group III. Tools

As in the previous groups, none of the analysed Tools contain all the criteria (Figure 21). In this case, the average percentage of criteria present is 22%, with EcoEffect, which contains 38% of the criteria, being the most complete, while Beat 2002 only contains 9% of the total criteria.

Analysing the data according to criteria and their corresponding categories (Figure 22) shows that this group only contains five, with criteria pertaining to (C4) Energy being the most prevalent, in 55% of Tools. In contrast, only 4% of criteria, on average, from category (C6) Social and Economic are considered by the methods in this group. This again underlines the greater concern of Tools for energy efficiency, as opposed to social and economic aspects (Haapio & Viitaniemi, 2008).

3.4. Comparative analysis of Level(s) with traditional methods

As indicated above, the final method included in this study was Level(s), which due to its characteristics cannot be included in any of the previous groups. However, given the importance that this instrument will have in Europe, we compared Level(s) and a representative method from each of the three foregoing groups using the identified variables (phase of life cycle for application; aspects of sustainability assessed; categories considered; and type and status of projects where assessment is applied). The three methods were selected based on the number of buildings and/or m^2 assessed, endorsement from the competent authority of the country of application, quality assurance background, and year of update. As a result, we selected LEED version 4.0 as the representative System, Passivhaus as the representative Standard, and ATHENA™ as the representative Tool. LEED version 4.0 (LEED v4) is the most used System worldwide (Bernardi et al., 2017), with presence in more than 165 countries and territories (LEED US, 2000); Passivhaus is the Standard with the greatest impact; and ATHENA™ (Cole, 2006) has more than 1200 different combinations of structural and enclosure models, enabling rapid assessment and comparison of the environmental implications involved in the development of a new building (or part of it).

In order to make this comparison, Table 12 identifies the relationship between the previous variables and methods, while Figure 23 highlights the percentage of the scope of each method according to the variables identified. The results obtained are discussed below.

Table 12. Relationship between the variables and methods.

variables		GI LEED v4	GII Passivhause	GIII ATHENA^{TM}	Level(s)
phase of life cycle applied	Desing	■	■	■	■
	Production	■		■	■
	Constrution	■		■	■
	Use	■	■		■
	Maintance	■		■	■
	Demolition			■	■
	Disposal	■		■	■
sustainability aspects assessed	Environment	■	■	■	■
	Society	■			■
	Economy	■			■
type and status of the project assessed	Existing building	■	■	■	■
	New building	■	■	■	■
	Residential building	■	■	■	■
	Office building	■	■	■	■
	Other type of building	■	■	■	
	Districts	■			
	Building product/component		■	■	
categories considered	(C1)Site and Sustainable Development	■			■
	(C2)Water	■		■	■
	(C3)Materials and Resource Consumption	■		■	■
	(C4)Energy	■	■	■	■
	(C5)Indoor Environmental Quality	■	■	■	■
	(C6)Innovation	■			■
	(C7)Social and Economy	■			■
	(C8)Service Quality	■			■
	(C9)Circular Economy	■			■
	(C10)Adaptation climate change				■

3.4.1.1. Phase of the life cycle in which assessment is applied

As shown in Figure 23, Level(s) assesses all the identified phases, in contrast to the Passivhaus standard, which only covers 29% of them, while the LEED System and the ATHENA™ Tool assess 86% of the phases of the life cycle. More specifically, Passivhaus focusses only on the phases of design and use of the building, while LEED ignores the phase of demolition, and ATHENA™ overlooks the phase of use (Table 12). However, the latter does accept data from simulations carried out with other instruments and simplifies the calculations for obtaining an LCA of a building, compared to the other methods.

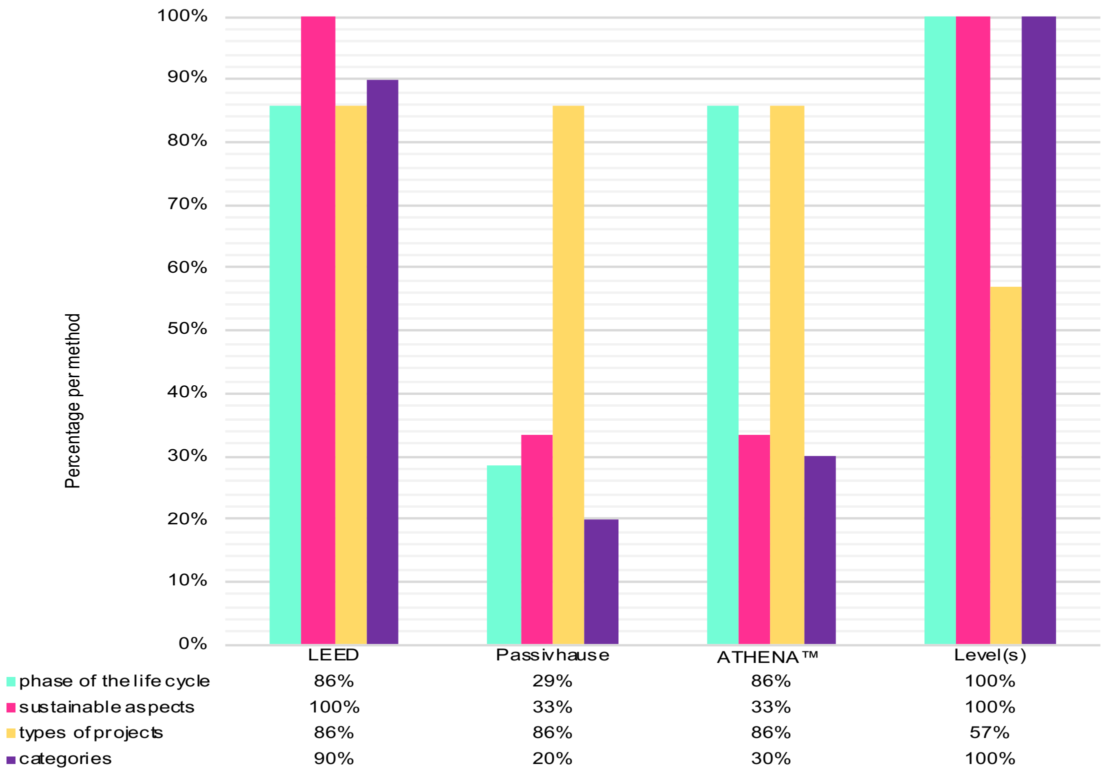


Figure 23. Percentage of the scope of each method according to the variables identified.

The inclusion of all phases in Level(s) means that the main agents responsible for a building adopt an cradle–to–grave approach to the life cycle, starting from the design phase (based on calculations, simulations and scenarios) and ending with the deconstruction of the building, and including the manufacture of products and materials used to construct the building, the construction of the building itself, the phase of use (measured according to the performance and satisfaction of occupants), and the reuse and recycling of materials. In addition, Level(s) is the only method to establish a link between the phases of the project and valuation-related aspects of the property, and provides information regarding the cost and economic benefit of each of the phases (Dodd et al., 2017b, 2017a).

3.4.1.2. Sustainable aspects considered

With regard to sustainable aspects, Figure 23 shows that only Level(s) and LEED cover all sustainable aspects. The Passivhaus standard and the ATHENA™ Tool address 33% of them, focussing only on the environmental aspect of sustainability (Table 9), and more specifically, energy consumption, high levels of thermal comfort and a catalogue of construction materials and systems that allow the above requirements to be met.

3.4.1.3. Assessment categories

In the case of categories, Level(s), again, is the only method to include all of them (Figure 23), followed by LEED, with 90% of categories assessed, whereas the Passivhaus standard only considers 20% of the identified categories.

Specifically, as indicated in (Table 12), the Passivhaus standard only takes into account categories (C4) Energy and (C5) Indoor Environmental Quality. In the case of ATHENA™, it can be observed that categories (C2) Water, (C3) Materials and Resources and (C4) Energy are once again the fundamental basis of this methodological group, facilitating the designer's choice of construction materials or systems that minimise the impact of the building on the environment. In the case of LEED, the concept of sustainability is more extensive than the two previous methods. Thus, although it only covers nine categories, it does include (C9) Circular Economy with the aim of optimising the use of resources, facilitating disassembly and the reuse (not recycling) of the materials, systems and subsystems that make up the building.

Finally, Level(s), as a more complete method is the only method to include category (C10) Adaptation to Climate Change. This is because one of the priority goals of the framework is to safeguard user health and wellbeing in estimated future climate conditions, taking into account an increased risk of extreme weather events, which may require consideration of the durability and strength of construction elements, or the increased risk of flooding, thereby considering the capacity of drainage systems and the strength of structures, among others (Dodd et al., 2017b, 2017a).

3.4.1.4. Types of projects where assessment is applied

Unlike the other variables studied, Level(s) in this respect is the method with the least coverage (Table 12); while LEED v4, Passivhaus and ATHENA™ assess 80% of the type or status of projects, Level(s) only assesses 63%, focussing exclusively on new-builds and refurbishment in the residential and tertiary (offices) sectors.

4. Discussion

From the foregoing analysis, we can conclude that since the 1970s, various strategies have been developed with the aim of reducing the energy consumption of buildings (Feist et al., 2005) and reducing losses. However, the introduction of the first BREEAM system signalled an attempt to rethink the concept of a building as a whole. Since then, the field of methods has seen a rapid increase in the number of instruments introduced into the global market (Cole, 2006).

However, based on the results of the foregoing analysis, despite the number of existing methods, whose ultimate goal is to achieve a construction or building that is unquestionably sustainable, differences in the way the different methods (regardless of the group to which they belong) address the various variables (phases of the life cycle, sustainable aspects, categories and types and statuses of projects) show that each of these methods individually fails to consider the complete study of the sustainable building. This is due, among other factors, to the year of development, the concept of sustainability in the country or region of application (Cole, 2006), the type of regulatory body, the interests of the agents involved, the evolution of the concept of sustainability, and the need to adapt methods to the construction industry in the country of application.

An analysis of the different variables suggests that the identified methods generally cover all the phases in the life cycle of a building, even though they may take a different approach and focus on different sustainable aspects and their corresponding assessment categories, especially the environmental aspect, and more specifically energy efficiency and indoor environmental quality. We can also observe how the social and economic approaches are far less prevalent, due in part to the limited knowledge or vagueness of the concept of sustainability itself, to the greater difficulty in assessing aspects and categories related to social and economic approaches, and to the fact that the methods traditionally focus on purely environmental sustainability. However, in recent decades, and especially since the year 2000, there has been a shift towards social and economic approaches, partly because construction activities are a social process.

The results have shown that the vast majority of the methods included in this study can be used to assess the majority of buildings, type and status of construction projects. Moreover, if we take into account the development date of the various methods, we can observe a marked increase in the number of type or status of projects assessed by these methods after the year 2000. This could be due to the fact that after using the initial instruments, the main agents involved realised that they needed specific versions that could be used to address different types of projects or components.

Based on the comparison between the four identified methods, and bearing in mind that LEED v4, Passivhaus and ATHENA™ are considered representative methods of the group to which they correspond, Figure 24 shows the global scope of Groups I, II and III and Level(s), and ranks the level of sustainability achieved by each according to four levels.

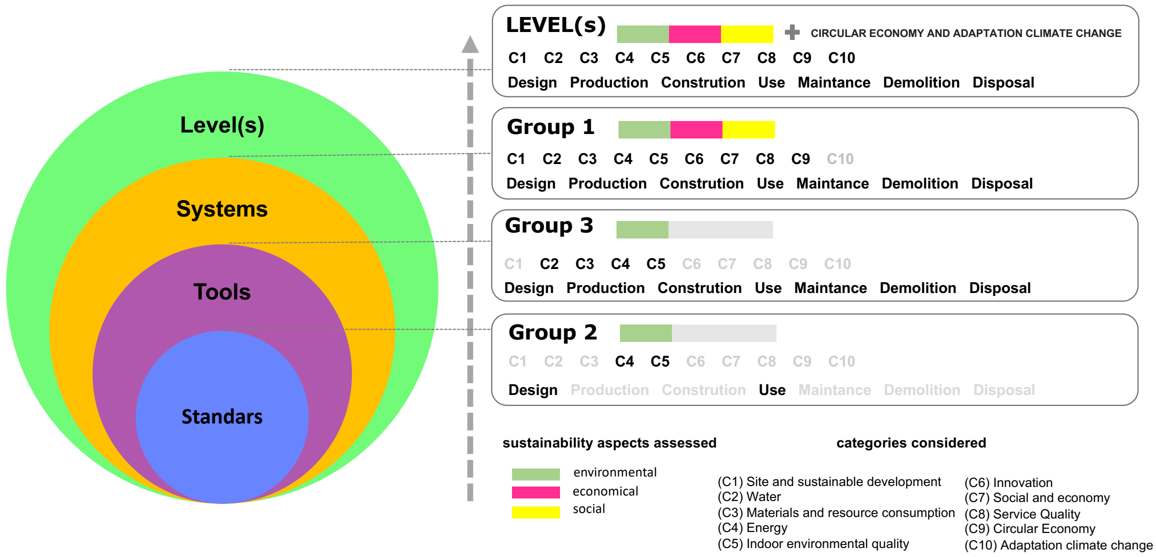


Figure 24. Relationships between Groups I, II, III and Level(s).

Finally, Figure 24 shows the relationship between the three groups and Level(s), according to the scope of the different study variables, based on the results obtained. As shown in Figure 24, Group II (Standards) only assesses two phases of the life cycle and the environmental aspect of sustainability, but like Group III (Tools) does not cover all the related categories, although the latter does cover all phases of the life cycle. Group I (Systems), cover the whole life cycle and the three sustainability aspects, but does not cover all the categories. It can be observed that only Level(s) covers all phases of the life cycle, all the sustainability aspects, and all the sustainable building categories. Level(s) includes the other three groups and is therefore the most complete assessment method to date.

5. Conclusions

Since the creation of the first tool for assessing building sustainability (TRNSYS, in 1975) up to the recent implementation of the European Level(s) framework, more than 600 methods have been developed. These have gradually been adapted to the sustainable building concept and aimed at assessing the various aspects of sustainability. All of them have played a transcendental role in the development of sustainable buildings by raising awareness of the main agents involved in recent years, even though their objectives, areas of application and structures are very different, depending on the country and launch date, as well as the aspects of sustainability they set out to address.

In this study, 36 of the 101 identified methods have been analysed. These were selected based on the number of m^2 certified to date, endorsement from the country of application, and the level of update. This analysis has evidenced the major differences between the three groups into which the most used methods can be classified (Systems, Standards and Tools), as well as Level(s). A comparison between the methods included in each of these groups has also been performed to select those with the greatest scope.

In conclusion, energy and indoor environmental quality, related to environmental aspects, are present in all the methods studied, which proves that these are the most influential, easily accessed aspects of sustainability compared to more recent social and economic aspects. Systems, in particular, are generally the methods that, to a greater or lesser extent, cover all aspects of a sustainable building. Nevertheless, not all the Systems cover all types of projects, nor assessment categories. In the case of the phases of the life cycle, however, it is the group with the greatest scope. By contrast, Standards are based solely on the environmental aspect of sustainability, focussing on criteria related to energy and indoor environmental quality, without including the other aspects prevalent in the modern concept of sustainable building. Moreover, they are only applied in two of the seven phases of the life cycle, i.e., the design and the use of the building. Tools are considered a halfway point between Systems and Standards, as they take into account both environmental and economic aspects, although the latter have little influence. In this case, not all the phases of the life cycle are covered; coverage is greater than in Standards, but less than in Systems. The comparative analysis of the variables studied (aspects, phases of the life cycle, categories, and type of projects) and criteria led to the conclusion that the most representative methods of each group are the following: LEED, in the case of Systems; Passivhaus, in the case of Standards; and ATHENA™, in the case of Tools.

Finally, the Level(s) tool, like Systems, assesses all the aspects of sustainable building, but unlike Systems it covers all the phases of the life cycle, as well as all the categories, including buildings within the circular economy framework. Moreover, it has the added value of considering adaptation and resilience to climate change. However, Level(s), for now, does not cover all the types of identified projects, as it is an instrument in the development phase. Therefore, the conclusion is that Level(s), currently in the testing phase, is the most complete method identified in this study, being based on earlier methods and designed to foster the adaptation of buildings to future climate changes and to encompass a broader concept of sustainable building.

Finally, this chapter, because of the large number of methods included in this study and the in–depth analysis made, is of great value to the main agents involved in sustainable building, giving them a clearer picture of the current assessment framework and enabling them to select the method which best responds to their needs.

PART II STRATEGIES TO DRIVE THE IMPLEMENTATION OF SBAMS

CHAPTER 3

Bases for the adoption of SBAM implementation strategies. The Level(s) case study[3]

[3] The results shown in this chapter were presented in: C. Díaz-López, M. Carpio, M. Martín-Morales, M. Zamorano. Defining strategies to adopt Level(s) for bringing buildings into the circular economy. A case study of Spain. Journal of Cleaner Production. 287 (2021). https://doi.org/10.1016/j.jclepro.2020.125048.

1. Introduction

In light of the results of the review of 101 SBAMs in the previous chapter, Level(s) is considered to be the most comprehensive and far-reaching method to date, with the assessment of the adaptation of buildings to climate change being one of its key features. Moreover, it is the only method to date with a European level strategy to promote its implementation throughout the EU. For this reason, given the diversity of the existing method, the adoption of strategies within the framework of this method will be addressed.

Level(s) is a common framework proposed by the EU and developed by the Joint Research Centre (JRC) for sustainable buildings, based on a comprehensive research effort involving both industry and the public sector. The tool aims to unite the entire value chain of the sector round a common European language for better building performance. To do this, it examines the complete life cycle of buildings.

This enables it to address their vast emission-reduction potential and circular resource flows, thus supporting the health and well-being of those for whom they are intended. All this is presented within the concept of EC and adaptation to climate change, moving away from the linear economic model of 'take, do and waste' (Dodd et al., 2017b, 2017a). Additionally, the establishment of unified indicators makes it easier to compare sustainable buildings within the EU. Consistent with this objective, the objectives set by Level(s) were as follows (Dodd et al., 2017b, 2017a):

- Raise awareness among the public, developers, and public procurement services of the need to have sustainable buildings and increase demand for them.

- Increase knowledge regarding the efficient use of resources within the built environment to foster better decision-making processes by designers, architects, developers, construction companies, construction product manufacturers, investors, and property owners.

- Provide a common EU approach to assessing the sustainability of buildings and the built environment. The flexible indicator can also be incorporated into new and existing evaluation systems.

Since Level(s) is based on the full range of existing tools (López et al., 2019), it is essential to analyse its potential as a critical tool for the development of a sustainable building within the framework of the CE and adapted to climate change in Europe. Understanding this novel indicator framework and its political, economic, administrative, and social environment impact (as well as that of its implementation) is vital to determining the need to apply this common language in various circumstances.

To meet all the above, the main objective of this chapter was to contribute to the existing body of knowledge in the field of sustainable building research, through the definition of strategies to adopt Level(s) for bringing buildings into the Circular Economy. Therefore, the strengths, weaknesses, opportunities and threats of Level(s) regarding the availability of resources, product quality, internal and market structure, consumer perception, among others, have been identified. This knowledge has made it possible to correct weaknesses, address threats, maintain strengths and exploit Level(s) opportunities for their correct implementation.

2. Materials and methods

The evaluation of Level(s) was carried out through the analysis Strengths, Weaknesses, Opportunities and Threats (SWOT), a tool that emerged in the field of economic analysis for the evaluation of management procedures in companies, projects and plans (Samolada & Zabaniotou, 2014), but whose use has been increasingly extended and applied in the context of environmental and sustainability research. SWOT facilitates the identification of factors that affect the use of Level(s), establishing the Weaknesses, Threats, Strengths, and Opportunities related to its implementation, facilitating future decision-making (Samejima et al., 2006) and informing decision–making, planning, and building strategies.

The main advantage of SWOT analysis is its simplicity (Liao & Chern, 2015; Zhou et al., 2019), which has led to its continued use in both leading companies and academic communities since its development in the 1960s (Ghazinoory et al., 2011). However, there are shortcomings in the traditional SWOT approach: (i) it produces a superficial and imprecise list of factors; based on the subjective perception of the selection of factors; and (ii) it lacks prioritisation of factors regarding the importance of each SWOT factor.

The first of the problems can be solved by selecting a panel of experts to reduce subjectivity in the identification of factors. The second, the absence of a prioritisation of these factors, has been solved with the proposal by several researchers based on the integration of SWOT with other quantitative methods – among which is the Analytical Hierarchy Process (AHP)–SWOT (Kangas et al., 2001; Kurttila et al., 2000). This approach was developed by Thomas L. Saaty (1987) (Saaty, 1987) and it is designed to solve complex problems of multiple criteria through the analysis of quantitative data relating to decision alternatives.

To achieve the main objective of this chapter, a triple SWOT–AHP–TOWS analysis was applied, an additional combination of analysis tools to further improve the decision-making process and also to develop policies based on the results of SWOT and AHP . It is one of the few models that allows the integration of analysis, identifying individual factor variables and appropriate policies (Gottfried et al., 2018). Hybrid SWOT–TOWS with AHP model are simple, efficient and the abilities to combine qualitative and quantitative criteria. Thus, AHP can manage the decision making in situation of uncertainty (Chanthawong & Dhakal, 2016).

Various fields of research have used such a three-phase analysis: tourism (Monavari et al., 2013), infrastructure projects (Behzad Malekpour Asl et al., 2020), biorefinery (Brunnhofer et al., 2019), forest (Kurttila et al., 2000), water resources (Gao et al., 2017), transport management (Dimić et al., 2016), textile industry (Dimić et al., 2016), among others. The SWOT method is based on expert judgement and is designed to identify the Weaknesses, Threats, Strengths, and Opportunities (SWOT) in order, subsequently, to prioritise factors identified through the AHP. Based on this information, the TOWS matrix has finally been used to generate strategies (Weihrich, 1982) to achieve to implementation of Level(s). Therefore, this three−phase analysis is suitable for this study since it allows the identification, through qualitative and quantitative methods, of the main strategies for the implementation of policies that promote improved construction within the framework of the circular economy.

The territory of Spain has been selected for this study, for its representation as a Mediterranean country, for its low percentage of sustainable construction development, as well as its high percentage of the urban population, among which the whole EU is the largest. 90% of the housing stock in Spain was built before the Technical Building Code, approved in 2006, came into force. Moreover, 60% of the properties were built without sustainability criteria, as no regulations existed at the time. For this reason, efforts to improve must be extreme. The working methodology described above, therefore, includes three distinct phases, as shown in Figure 25:

(i) application of the SWOT analysis;

(ii) application of the AHP method, both supported by the Delphi method;

(iii) establishment of strategies base on TOWS matrix. These phases are described below, as well as the Delphi method on which they are based.

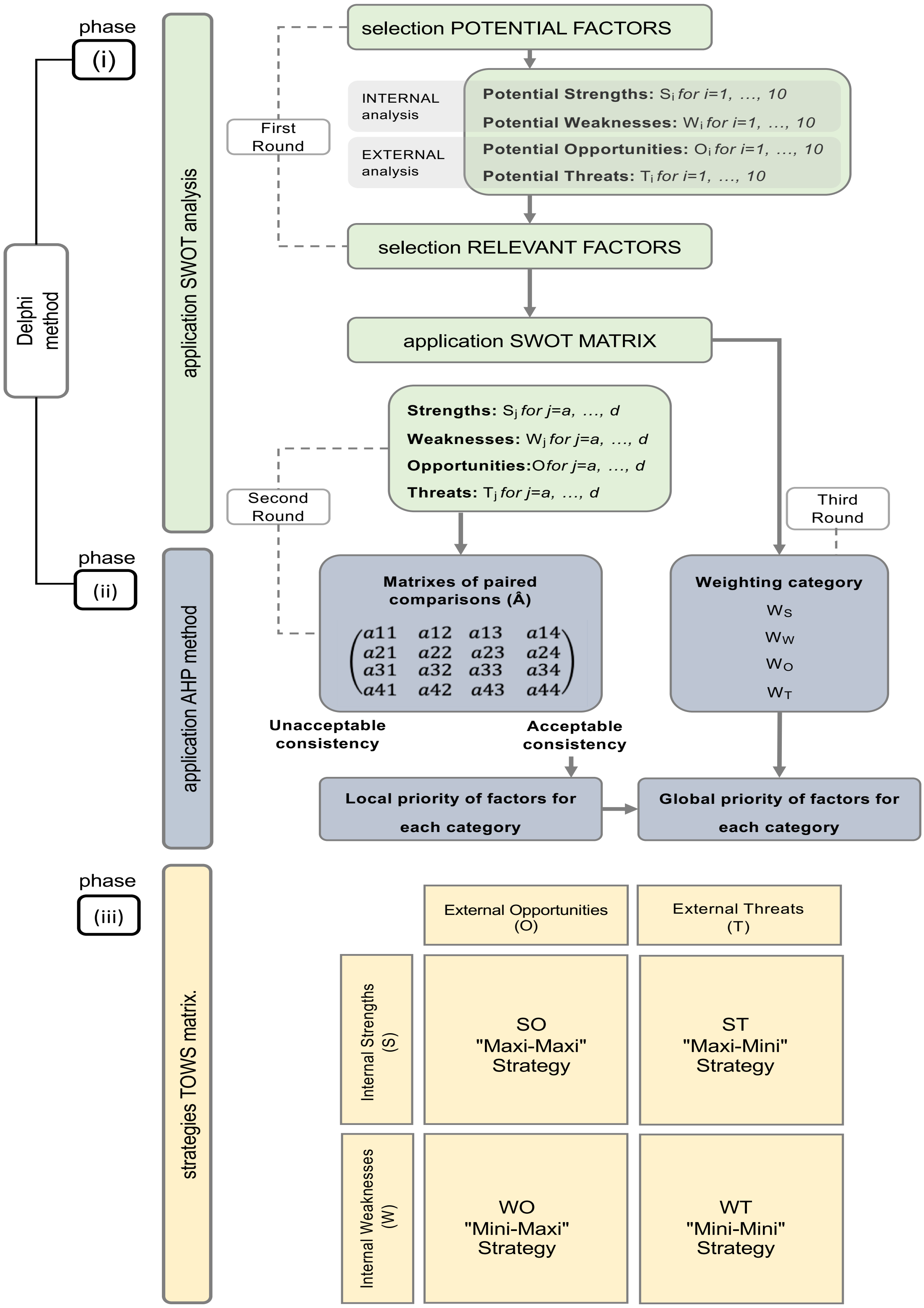


Figure 25. Materials and methods.

2.1. Implementation of the SWOT analysis.

Application of the SWOT analysis, in aggregate, is based on both internal and external analyses. Internal analysis facilitates the identification of Strengths and Weaknesses, controllable factors that support and hinder the implementation of Level(s), respectively; external analysis identifies Opportunities and Threats, uncontrollable factors that allow and incapacitate the achievement of the objectives set out in Level(s) (Dyson, 2004). Initially, and based on the technical manuals provided by the developers of Level(s) (Dodd et al., 2017b, 2017a), a set of potential factors was selected. Subsequently, those who will be included in the SWOT matrix will be selected based on the opinion of the experts, and those who will be called relevant factors. To gather the opinion of the experts, a survey was designed in which these persons were asked to rate, from '1' to '10', the degree of importance of each of the possible factors selected, considering '1' as minor and '10' as very important.

2.2. Application of the *AHP* method.

Once the SWOT matrix was defined, it was prioritised using the quantitative AHP method, allowing the SWOT factors to be ranked according to their relative importance. AHP is based on the own value method (Kilinç et al., 2018; Lyu et al., 2020; Moussaoui et al., 2018), and as a result of the calculations, each of the SWOT factors has been associated with a local priority level or index p (0 < p < 1, $\sum_{i=1}^{n} p_i = 1$) within a group of n relevant factors that integrate each of the categories Weaknesses, Threats, Strengths and Opportunities, as well as a total priority index q (0 < q < 1,

$\sum_{j=1}^{4n} q_j = 1$) in the group of 4n factors that integrate the entire SWOT matrix. To this end, a new survey was designed which was then sent to the experts involved and in which a peer comparison was requested between the factors included in the SWOT matrix, for each of the categories, as well as between categories, according to the scale of comparisons recommended by Saaty (1987) (Saaty, 1987) and presented in Figure 26. It shows that, for the paired comparison, the scale was limited to odd numbers and varied from 9:1 (the F1 factor is much more critical than the F2 factor), at 1:9 (the factor F2 is much more important than the factor F1); for 1:1 the factors are equally important (Wang & Chen, 2014).

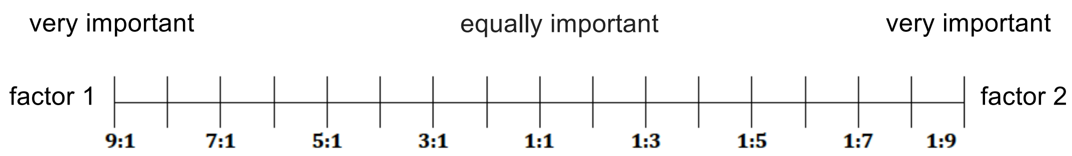


Figure 26. Scale for pairwise comparisons.

To calculate the local priority index (p_j), firstly four factors were selected for each of the category; as result four original square matrices A, with dimension 4 × 4 (a_{ij} is the element that takes up row *i* and column *j*, for *i* = 1, ..., 4, and *j* = 1, ..., 4), were obtained with the average value of the experts' opinions, according to the Equation 1. In a second step the matrices of paired comparisons $\hat{A}$ in which $\hat{a}_{ij}$ is the measure of the preference of the alternative in row *i* when it is compared to the alternative of column *j* (Equation 2). Finally, each element of each matrix $\hat{A}$ was normalized to obtain the normalised paired comparison matrix $\hat{A}_n$; to do that each element has been divided by the addition of its column; the obtained value v_j

(Equation 3) turned out to be the local priority of factors (p_j), in each category.

$$A = (a_{ij})_{i,i=1,\ldots 4} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \quad (1)$$

$$\hat{A} = (\hat{a}_{ij})_{i,j=1,\ldots,4} = \begin{pmatrix} \hat{a}_{11} & \hat{a}_{12} & \hat{a}_{13} & \hat{a}_{14} \\ \hat{a}_{21} & \hat{a}_{22} & \hat{a}_{23} & \hat{a}_{24} \\ \hat{a}_{31} & \hat{a}_{32} & \hat{a}_{33} & \hat{a}_{34} \\ \hat{a}_{41} & \hat{a}_{42} & \hat{a}_{43} & \hat{a}_{44} \end{pmatrix} \text{where } \hat{a}_{ij} = \begin{cases} 1, & i = j \\ a_{ij}, & i < j \\ 1/a_{ij}, & i > j \end{cases} \quad (2)$$

$$v_j = \frac{1}{4} \times \sum_{i=1}^{4} \frac{\hat{a}_{ji}}{c_i} \quad (3)$$

The total priority index for each factor (P_j) has been calculated taking into account Equations 4, where WG is the weight corresponding to the category of the factor, and v_j is the value of its local priority, with j = 1, ..., 4. The weight of each category (WS, WW, WT, WO) was determined as the weighted average of the experts' opinions.

$$P_j = W_G \times v_j \quad (4)$$

Finally, an important consideration in terms of the quality of the final decision concerns the consistency of that judgement, as displayed by the decision-maker during the series of paired comparisons. It should be kept in mind that perfect consistency is tough to achieve, and that some inconsistency is expected in almost any set of paired comparisons, as they are judgements derived by people. The AHP offers a method for measuring the degree of consistency between the paired options provided by the decision-maker. If the degree of consistency is acceptable, the decision-making process can be continued. If it is unacceptable, the decision-maker must reconsider and possibly modify his/her judgement on paired comparisons before continuing with the analysis. This was done using the Consistency Ratio (CR), designed so that values exceeding 0.1 were a sign of inconsistent judgement and calculated according to the methodology established by Saaty (Saaty, 1987). The CR of a matrix was calculated by applying Equation 5, where CI is the consistency index of the matrix, RCI is the random consistency index of the matrix, n is the number of factors (n=4), and nmax is determined as the sum of the elements of the local priority vector v_j.

$$CR = \frac{CI}{RCI} = \frac{\frac{n_{max} - n}{n-1}}{\frac{1.98 \times (n-2)}{n}} \quad (5)$$

2.3. Determination of Strategies

The most straightforward approach to generating these strategies, having developed the SWOT–AHP analysis, is the TOWS matrix (Turcksin et al., 2011). Weihrich (Weihrich, 1982) developed TOWS as the next step of SWOT analysis. This tool analyses the key actions that will need to be taken to Correct Weaknesses, Address Threats, Maintain Strengths, and Exploit Opportunities. Four types of strategies have been considered:

- **Offensive Strategies**. These are obtained by relating Strengths + Opportunities (SO). They are growth strategies that seek to link internal and external strengths to improve the situation. These are known as maxi-maxi strategies as they have the highest potential.

These strategies use strengths to take advantage of opportunities.

- **Defensive Strategies.** These are obtained by relating Strengths + Threats (ST). They are reactive strategies that link internal strengths to counter external threats. These are known as maxi-mini strategies.

- **Adaptive Strategies**. These are obtained by relating Weaknesses + Opportunities (WO). There are reorientation strategies where some element of weaknesses is changed to take advantage of opportunities. These are known as mini-maxi strategies.

- **Survival Strategies.** These are obtained by relating Weaknesses + Threats (WT). These are known as mini-mini strategies as they have the least potential. These strategies minimize weaknesses to avoid threats.

2.4. Delphi method

Both the determination of the SWOT matrix and the application of the AHP methodology are based on the Delphi method. Delphi is a forecasting technique involving the compilation of knowledge from a selected group of experts (Dalkey & Helmer, 1963), enabling solutions to interdisciplinary research problems where the opinions of the experts are heterogeneous (Stern et al., 2012; Sutterlüty et al., 2017). It consists of a strong consensus through a process of repetitive evaluation with controlled feedback of opinion (Landeta, 2006). This method is used mainly in cases where critical information is indispensable (Rowe et al., 1991). Its main characteristics are anonymity, iteration, and controlled feedback (i.e., the response of the group in statistical form and heterogeneity). In this study, the Delphi technique has been applied in the following four phases:

I. Definition of objectives. This presents a formulation of the problem, the objective of the study and the spatial frame of reference.

II. Formation of the panel. There is no defined guide to determine the number of participants or their level(s) of experience (Rikkonen & Tapio, 2009). However, choosing the right participants to serve as experts is fundamental to Delphi's research: the quality of the experts is directly related to the quality of the results. For this reason, a highly selective process has been used to identify panellists. This phase presents a qualitative dimension, where respondents were selected based on the predetermined objectives and because of experience criteria; and a quantitative dimension, where the choice of sample size varied depending on the resources and time available. To reduce the risk of illusory experience and to systematise the process for identifying experts, in this work the selection of experts was based on those defined by Atherton et al. (Atherton, 1976) and its Knowledge Resource Nomination Worksheet (KRNW), which enabled the establishment of the following four steps:

- In a first step, different categories of experts were proposed for this study: universities, students, and research centres; builders and developers; governmental agencies (local, autonomous, state and international); professional associations and institutes of construction and organisations for sustainability; technical professionals of the building; consultants and advisors in sustainability and environment; manufacturers; environmental and ecological associations; manufacturers; and business associations. Atherton *et al.* (Atherton, 1976) emphasised that it is essential not to write down the specific names of the experts at this stage.

- In a second step, the categories were supplemented with the names of experts based on their research in that area and in–field experience.

- In a third step, the classification of experts by qualifications was then carried out, for which the ratings of the first roster of experts (second step) were compared and ranked by priority for the invitation to the study. First, many sublists as categories were created; the experts were then classified by those sublists according to their qualifications. Each member of the research team then classified each subcontractor independently, according to the person's qualification. Based on the classifications, a panel was created for each of the 10 categories, resulting in a total of 190 experts (Table 13).

- Finally, the experts were invited to participate in the study. This was done through e–mail, which included a brief explanation of the background, objectives, and expected results of the study.

Table 13. Detailed composition of the panel of experts.

Category	Number of experts					
	First phase		Second phase		Third phase	
	Sent	Answers	Sent	Answers	Sent	Answers
Universities, students and research centres	50	23	23	21	6	6
Builders and promoters	20	11	11	9	3	3
Administration						
Local	15	11	11	9	3	3
Autonomous	10	6	6	4	2	2
State	10	7	7	3	1	1
International	5	1	1	-	-	-
Professional associations and institutes of construction and organisations for sustainability	10	7	7	6	2	2
Technical professionals of the building	30	22	22	18	2	2
Sustainability consultants	10	9	9	8	3	3
Manufacturers	15	9	9	7	3	3
Environmental associations	5	2	2	1	1	1
Administration of the real estate	5	2	2	1	1	-
Business partnership	5	2	2	1	1	-
Total	190	112	112	88	28	26

III. Preparation and launching of questionnaires. The questionnaires were designed to facilitate responses by respondents. The questions were based on the objectives of the work and followed a clear, concise and robust approach. The design of the questionnaires aimed to capture the diversity of opinions, achieve a high degree of reliability, allow the involvement of the experts, avoid the prominence of one or more experts over others, guaranteeing equal participation and find the formation of a criterion with a high level of objectivity.

In this study, a three–round Delphi survey (Table 11) was conducted; each round involved a written survey of participants followed by statistical feedback for each survey question. After seeing the results of the previous round, participants were asked to reconsider their views. Using this method, there typically is a convergence of opinions after three or four rounds, from which a stable group opinion emerges (Tavana et al., 2012). In the First Round, a two–pronged approach (involving both qualitative and quantitative methods) was applied. For this purpose, an online questionnaire containing various types of questions was developed. The tool allowed evaluating, on the one hand, the quality of the experts and, on the other, qualitatively selecting the relevant factors from among the potential factors. In the second round, peer comparison of relevant SWOT factors and an AHP were applied to quantify and weight Level(s) factors. Finally, in the third round, the questionnaire incorporated a peer comparison of the four SWOT groups.

IV. Exploitation of results. The aim of the successive questionnaires was to reduce dispersion and clarify the average consensus opinion. In the second dispatch of the questionnaire, the experts were informed of the results of the first consultation and had to provide a new response, which allowed the reasons for the differences to be identified and evaluated. Iterations of the process continue until it is perceived that an absolute consensus and/or an acceptable level of stability in responses has been reached. The outcome of the last round can be considered the final response of the expert group. The level of consensus reached after each round determines whether there is a need to start an additional round in the research process. The coefficient of variation (VoC), calculated by the quotient between the standard deviation (SD) and the average of the responses, has been considered for its determination. If the Voc is less than 0.5, the internal agreement is considered reasonable (Zinn et al., 2001).

3. Results and discussion

Following the established methodology (Figure 25), the results obtained are presented below. The SWOT analysis will be presented first, followed by the AHP methodology, followed by the results concerning the quality of the opinion process established by a Delphi methodology. Finally, based on the analyses carried out, the strategies generated to facilitate the implementation of Level(s) have been presented.

3.1. Implementation of the SWOT analysis.

The SWOT matrix (Figure 27), which provides a qualitative analysis of the application of Level(s), has been obtained in two phases. The first of these (internal and external analysis) has made it possible to obtain a list of potential factors for each of the categories involved in the SWOT matrix. In a second phase and thanks to the support of experts, the most relevant factors will be selected from these factors, which will form the SWOT matrix. The results obtained in this phase, which are presented and analysed below, are presented in Tables 14 and 15, as well as in Figure 27.

Table 14. Assessment of potential factors from expert surveys. Internal analysis: Identification of Strengths and Weaknesses (Part 1).

Potential factor		Description	A[1]	P[2]
Strengths				
S_a	Support from the EU(EC).	It is driven and supported by an important common public body such as the EC.	8.482	2nd
S_b	Support from different associations at European level.	There are a number of influential actors with a strong interest in its development, such as GBC, professional associations, companies and national governments.	7.748	8th
S_c	Its design is oriented to cover a broad spectrum of actors, with capacity, experience, activity, objectives or diverse interests	The breadth of potential users increases their ability to expand. Potential actors would be property owners, development agents and investors, design teams (among others, architects and engineers), construction and demolition management personnel, property agents and appraisers, asset and facility managers, public and private organizations using the evaluated buildings, etc.	8.098	5th
S_d	It is a common reference language for the whole of Europe, enabling progress on sustainable building to be compared.	Being able to access a European framework with a language and methodology common to all countries about sustainable construction, allows the creation of European and other national policies along the same lines, joining forces in its dissemination.	8.652	1st
S_o	Allows use in multiple situations; can be used in the different phases of the life of the buildings and for different types of actions: new construction and rehabilitation.	Level(s) has been designed to be used in the different phases of the life of a building, allowing the transition from simple to more complex and complete calculations, identifying key steps to improve to reduce the environmental impact, which multiplies its use opportunities.	8.321	3rd
S_f	It is based on the three current key aspects of sustainability policies.	Level(s) covers the three keys of sustainability: environmental (through life cycle analysis), economic (with emphasis on circular economy), and social (health analysis), so it aligns perfectly with the upcoming European initiatives, demonstrating its relevance for implementation.	8.223	4th
S_g	Level(s) would allow progressive implementation of the objectives.	The structure of the tool would allow, if necessary, to facilitate implementation, the possibility of implementation in several phases of the different objectives, starting for example with the most urgent, developed or extended -as carbon footprint or healthy spaces-, and add the rest later.	7.902	6th
S_h	It allows a partial or total implementation of double character: obligatory or voluntary.	In this way the most important indicators could be made regulatory, while those who might present more difficulties could be established on a temporary basis as volunteers to facilitate the preparation of the sector for their management.	7.518	7th

[1] Average valuation; ,[2] Position by category

Table 14. Assessment of potential factors from expert surveys. Internal analysis: Identification of Strengths and Weaknesses (Part 2).

potential factor		description	A[1]	P[2]
Weaknesses				
W_a	Complexity of use guides.	For now, Level(s) guides are complex and not very didactic. It makes it difficult to understand them and ultimately to use them by the wide range of agents to which they are addressed (designers, developers, builders, manufacturers, users, etc.)especially for those whose professional work does not involve direct experience with the concepts handled in the analyses.	8.126	1st
W_b	Difficulty in agreeing on the Level(s) approach to actors in professional contexts from different countries.	As it is a framework for the whole of Europe, it is necessary to find consensus for its acceptance by actors from a wide range of professional and cultural, and even environmental and climate contexts.	7.649	5th
W_c	Reliance on other tools to obtain data.	The need to rely on external measuring tools of varying technical utility to obtain some data needed for analysis may condition its ease of use.	7.468	6th
W_d	The comparative ability of Level(s) depends a lot on the criteria used in each evaluation.	Without reference values to compare the data, it is difficult to draw direct conclusions and the comparison is only effective with other buildings with similar evaluator criteria and building characteristics.	7.928	3rd
W_e	Mainly quantitative nature of the analysis.	The analytical approach based mainly on quantifiable data may discourage their use intentional professionals by not helping them to develop or demonstrate the validity of those sustainable strategies, architectural design, of a more qualitative character, but of great efficiency to obtain positive results.	7.045	7th
W_f	Methodology not very self-sufficient and therefore dependent on other procedures or databases.	In order to achieve some objectives, set out in Level(s), it is necessary that there be prior systemic changes in some commercial activities involved in building, such as the provision of environmental product declarations for the correct assessment of LCA (life cycle analysis) and LCC (life cycle costs).	7.712	4th
W_g	Sample results with data only.	The way in which results are displayed exclusively through technical data, difficult to assimilate by some non-expert agents such as building users, can produce disinterest and drive away these types of actors who are key in the success of the tool's welcome.	7.036	8th
W_h	Difficulty in developing a comprehensible, effective and useful implementation for the end user.	There is a risk that users and/or promoters will see that evaluation with Level(s) is just a process that increases cost and effort without contributing anything in return, for example, in some cases with the energy performance certificate.	8.063	2nd

[1] Average valuation; ,[2] Position by category

Table 15. Assessment of potential factors from expert surveys. External Analysis: Identification of Opportunities and Threats (Part 1).

Potential factor		**Description**	**A[1]**	**P[2]**
Opportunities				
O_a	Relationship between environmental awareness and the use of Level(s).	The use of Level(s) generates more excellent knowledge of the professionals of the sector and its clients, on the impact of construction on the environment, resulting in a positive feedback cycle whereby higher environmental sensitivity drives knowledge about Level(s), and the use of this, in turn, promotes such sensitivity.	7.730	8th
O_b	Possibility for different agencies to disseminate it by including it in their proposals.	By being included in certification and regulatory tools at different scales across Europe, the bodies associated with these tools and regulations will drive their development by taking ownership of them.	7.847	3rd
O_c	Act as a spearhead and reference point for sustainable initiatives.	Being a pioneering and ambitious project in terms of scope and impact, it can be a reference action for sustainability and circular economy policies in general, encouraging its initial impetus and development, and their settlement as an example of methodology.	7.784	4th
O_d	The growing ecological awareness of the citizens encourages their conversion into political initiatives.	That in Europe, there is a growing demand for and awareness of sustainable development throughout society, supports and legitimizes the incorporation of Level(s) in concrete policies and regulations.	7.764	7th
O_e	It will facilitate and disseminate the standardization of desirable comfort standards by users, which will increase the demand for Level(s) buildings.	Buildings designed under the criteria determined by Level(s) will offer standards of comfort that will be of tangible benefit to society as a whole, and which, once extended, will be difficult to renounce, making the reception of the tool extensive and practically definitive and irreversible, as is already the case with some improvements introduced by the changes in the technical codes of the building.	7.782	5th
O_f	It responds to the need to adapt buildings to climate change.	The changing climatic conditions will make any measure to adapt to them essential and Level(s) can represent the most effective and feasible way to face them from the building field.	8.136	1st
O_g	Build on the experience of existing sustainability certification tools.	Voluntary sustainability certification tools, already operational in all European countries, are an example of the feasibility of building construction by assessing most of the indicators provided by Level(s), and with ambitious compliance requirements.	7.771	6th
O_h	Alignment with sustainable and circular economy initiatives and policies.	The Level(s) approach, fully integrated into the circular economy idea, makes the activities involved and the products developed in the processes that have used Level(s) can justify their sustainability and circularity to obtain tax advantages and other benefits that are emerging to drive change.	8.064	2nd

[1] Average valuation; ,[2] Position by category

Table 15. Assessment of potential factors from expert surveys. External Analysis: Identification of Opportunities and Threat (Part 2).

Potential factor		Description	A[1]	P[2]
Threats				
T_a	Loss of potential due to failure to implement regulations.	If it does not become a European directive or if it does not reach regulations and regulations in the various Member States, and remains a purely voluntary framework, it risks losing its full potential to extend itself as a frame of reference.	8.495	1st
T_b	If it is not implemented quickly enough to meet the objectives and deadlines of the Paris Agreement, its effectiveness as a tool for change could be called into question.	Moreover, with it, the work and resources invested in a project of that size.	7.636	5th
T_c	Possible rejection, due to the inertia of the market and its difficulty to adapt to changes.	The difficulty of a large part of the construction and building market, in general, to adapt to a sustainable model can provoke rejection of its implementation and therefore, opposition or lack of support from that sector.	7.559	7th
T_d	There is a danger that to obtain a better reception of the project from specific sectors, extreme flexibility in criteria will lead to a loss of potential as a tool.	Trying to satisfy those actors involved with the most significant resistance to the change of model can lead to a weak framework, without the capacity to achieve sustainable development goals and therefore to question their usefulness and expansion.	7.505	8th
T_e	Uncertainty in the data needed to carry out the analysis.	In some cases, these data do not exist (2030-50 climate files), or are incomplete (manufacturers' environmental product declarations), or are unreliable (material databases).	7.883	2nd
T_f	Possibility of a complementary relationship with existing certification tools.	Poor alignment between Level(s) and current voluntary certification tools could lead to the perception of Level(s) implementation as a duplication of work without duplicating benefits, or even as competition for such tools.	7.582	6th
T_g	Possible inability to reach consensus among all European countries on the criteria and factors of the Level(s) analysis.	Climate change and resource scarcity will affect the different Member States in a variety of ways, so the needs and priorities for assessment will also be different, and disagreement along these lines could affect an adequate standard reception.	7.802	4th
T_h	Possible reluctance about the need for a systemic change in the approach and way of working for the majority of the sector.	Sustainable building implies a new way of understanding and making buildings for the whole sector, based on the circular economy so that all parts of the process are dependent on each other. The change for many professionals from working isolated to the need to consider multiple parts and factors involved in the process, can cause resistance or even lead to simplistic and appealing interpretations that limit, reduce or nullify the potential of the tool.	7.820	3rd

3.1.1. Internal and External Analysis. Potential Factors

To determine the potential factors for each of the four categories involved in the SWOT matrix, the technical manuals provided by the Level(s) developers have been used (Dodd et al., 2017b, 2017a). From these, a total of 16 potential internal factors related to Level(s) were selected, which are controllable and cannot be modified in the short term. Half were identified with internal aspects that facilitate the development and implementation of Level(s) (Strengths) and half were aspects that make its effectuation difficult (Weaknesses). In the same way, a total of 16 external and uncontrollable potential factors were selected, eight of which will facilitate the development of Level(s) (Opportunities), and another eight that will impede such progress (Threats). On the other hand, the potentially external factors were considered aspects that were not yet concrete, representing opportunities or threats for the development of Level(s) in Spain.

Tables 14 show the selected factors. It may be noted as being driven and supported by a critical common public body such as the EU, which strengthens commitment and collaboration between academic research, business, industry professionals and government institutions; this is a subjective aspect that facilitates its development and implementation. Similarly, the fact that there is a growing demand for and awareness of sustainable development throughout society in Europe supports and legitimises the incorporation of Level(s) into concrete policies and regulations. This is an external aspect, which facilitates its development and implementation. On the contrary, the dependence on other tools to obtain the data is considered a weakness that cannot be modified in the short term. This fact may condition its ease of use, which, together with the complexity of the guides, may result in a handicap that further enhances the uncertainty in the data needed to carry out the analysis.

3.1.2. Determination of the SWOT Matrix. Relevant Factors

Having identified the 32 potential factors in the previous section, a qualitative approach was adopted to construct the SWOT matrix, based on input from the panel of experts. To this end, in a first round of the Delphi method (Table 13), respondents were asked to attach importance in each category (Strengths, Weaknesses, Opportunities, and Threats), between '1' and '10', to the potential factors identified in the previous stage and listed in Tables 14 and 15. This allowed selection of the 16 most important factors, i.e., eight internal relevant factors (four Strengths and four Weaknesses) and eight external relevant factors (four Opportunities and four Threats) that were denominated, respectively, as S_i, W_i, O_i, and T_i, for i={1, 2, 3, 4}.

The relevant factors allowed obtaining the SWOT matrix (which compiles all the aspects mentioned by the interested parties, as shown in Figure 27). This framework yielded interesting initial information on Level(s). Thus, they were highlighted as positive aspects (not contemplated in the rest of the current SBAM) (Díaz López et al., 2019); their character as a common framework, the support of the European Commission; and evaluation of the adaptation of buildings to climate change within the concept of the Circular Economy. On the other hand, the complexity of the user guides; difficulty in developing a comprehensible, practical and useful implementation for the end–user; and dependence on other databases are negative aspects compared to other SBAMs applications such as VERDE or LEED.

STRENGTHS (+)	WEAKNESSES (-)
It is a common reference language for the whole of Europe that allows us to compare progress in sustainable building.	The complexity of user guides.
Support from the European Commission (EC).	Difficulty in developing a comprehensible, effective and useful implementation for the end-user.
Allows use in multiple situations; can be used in the different phases of the life of the buildings and for different types of actions: new construction and rehabilitation.	The comparative ability of Level(s) depends a lot on the criteria used in each evaluation.
It is based on the three current critical aspects of sustainability policies	Methodology not very self-sufficient and therefore dependent on other procedures or databases.
OPPORTUNITIES (+)	**THREATS (-)**
It responds to the need to adapt buildings to climate change.	Loss of potential due to failure to implement regulations.
Alignment with sustainable and circular economy initiatives and policies.	Uncertainty in the data needed to carry out the analysis.
Possibility for different agencies to disseminate it by including it in their proposals.	Possible reluctance about the need for a systemic change in the approach and way of working for the majority of the sector.
Act as a spearhead and reference point for sustainable initiatives.	Possible inability to reach consensus among all European countries on the criteria and factors of the Level(s) analysis.

Figure 27. SWOT matrix.

3.2. Application of the AHP method

The SWOT matrix thereby obtained enabled a global and qualitative analysis of strengths and weaknesses, but not their quantification. Therefore, application of the AHP in this study has been aimed at the quantitative evaluation of the factors comprising the SWOT matrix. This made it possible to prioritise them both locally and globally. The results obtained, displayed in Table 16 and Figures 28 and 29, are analysed and discussed below.

Table 16. Local and global priority indexes and position for each factor.

	relevant factor		local priority index		total priority index	
			Value (p_j)	Position	Value (P_j)	Position
STRENGTHS ($W_{S=0.3887}$)	S_2	It is a standard reference language for the whole of Europe that allows us to compare progress in sustainable building.	0.2920	1st	0.1135	2nd
	S_3	Allows use in multiple situations; can be used in the different phases of the life of the buildings and for different types of actions: new construction and rehabilitation.	0.2791	2nd	0.1085	3rd
	S_1	Support from the EC.	0.2406	3rd	0.0935	5th
	S_4	It is based on the three current critical aspects of sustainability policies.	0.1884	4th	0.0732	7th
WEAKNESSES ($W_{W=0.1088}$)	W_4	Difficulty in developing a comprehensible, practical and useful implementation for the end-user.	0.3278	1st	0.0357	11th
	W_1	The complexity of user guides	0.2317	2nd	0.0252	14th
	W_3	Methodology not very self-sufficient and therefore dependent on other procedures or databases	0.2293	3rd	0.0249	15th
	W_2	The comparative ability of Level(s) depends a lot on the criteria used in each evaluation.	0.2113	4th	0.0230	16th
OPPORTUNITIES ($W_{O=0.3720}$)	O_3	It responds to the need to adapt buildings to climate change.	0.3174	1st	0.1181	1st
	O_4	Alignment with sustainable and circular economy initiatives and policies.	0.2884	2nd	0.1073	4th
	O_1	Possibility for different agencies to disseminate it by including it in their proposals.	0.2030	3rd	0.0755	6th
	O_2	Act as a spearhead and reference point for sustainable initiatives.	0.1912	4th	0.0711	8th
THREATS ($W_{T=0.1305}$)	T_1	Loss of potential due to failure to implement regulations.	0.2924	1st	0.0382	9th
	T_4	Possible reluctance about the need for a systemic change in the approach and way of working for the majority of the sector.	0.2769	2nd	0.0361	10th
	T_3	Possible inability to reach consensus among all European countries on the criteria and factors of the Level(s) analysis.	0.2347	3rd	0.0306	12th
	T_2	Uncertainty in the data needed to carry out the analysis.	0.1960	4th	0.0256	13th

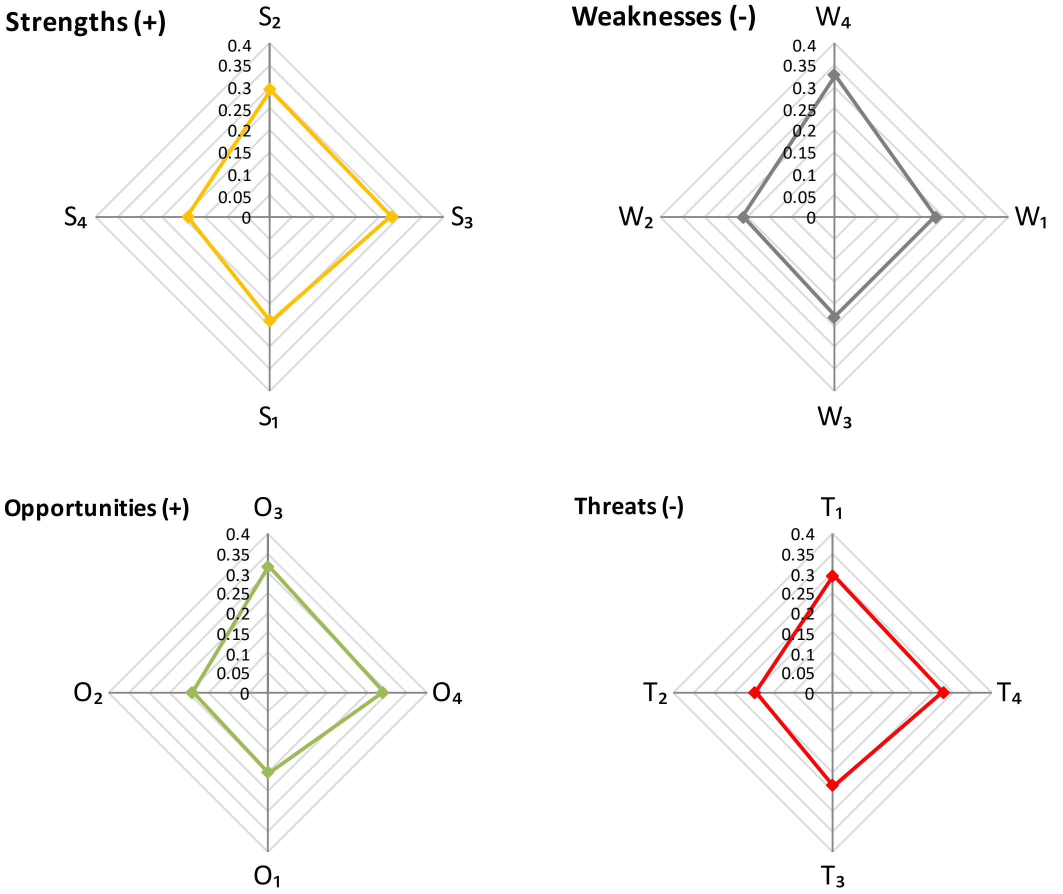


Figure 28. Local priority of factors.

3.2.1. Determination of local priority index

As shown in Table 16, for each of the factor categories in the SWOT matrix, the local priority index has been determined. This allowed us to know and quantify the greater or lesser weight the experts have given to the relevant factors. In the following section, the results for each category are analysed and discussed.

Strengths (+). Figure 28a shows very similar values in the local priority indices obtained for the four strengths included in the SWOT matrix. However, the prioritisation of factors is situated in the first place the S_2 strengths (p_{S4}=0.2920). This indicates that Level(s) is a standard reference language for the whole of Europe that allows us to compare progress in sustainable building.

On the other hand, the factor S_4 (It is based on the three current critical aspects of sustainability policies) is the factor that has obtained the lowest value (p_{S2}=0.1884). The SBAMs used so far have shown that each of them separately does not assess all aspects of a sustainable building. Many assess energy and the quality of the interior environment; few assess more recent social and economic aspects. In fact, the very concept of sustainable building has evolved. It should be noted that the emerging theme, social aspects, has been the last to be incorporated (C. Díaz-López et al., 2019).

It is worth highlighting the S_3 strength p_{S3}=0.2791. Interest in including the most significant number of phases in a building's life cycle is reflected in the evolution of methodologies. Consequently, although until its appearance Level(s) was the only tool that included all of them, method such as the ATHENA™ Tool or LEED covered all except one: its use and demolition, respectively (López et al., 2019). This is why it is justified that this factor shows a slightly lower value than the first.

Weaknesses (−). Figure 28b also shows, in this case, very similar values with respect to barriers that can affect the excellent development of Level(s) (although it stands out, with a p_{W4}=0.3278, the factor W_4). Which identifies the difficulty of developing an understandable, practical, and useful implementation for the end-user. This weakness is followed by W_3, with a local index p_{W3}=0.2293. It identifies the condition that this is an insufficiently self–sufficient methodology, dependent on other procedures or databases that require the use of external measurement tools of varying technical utility to obtain some data needed for analysis, which identifies the difficulty of developing an understandable, practical, and useful implementation for the end–user.

Finally, the weakness that least worries the experts has been the W_2, with a local index p_{W2}=0.2113. In this case, the experts question the comparative capacity of Level(s) which, in the absence of benchmarks against which to compare the data, makes it difficult to draw direct conclusions. Consequently, the comparison is only valid with other buildings whose criteria of the evaluator and characteristics of the building are similar.

Opportunities (+). Figure 28c and Table 16 show a local priority index for the opportunities assessed by the experts, with a significantly higher value for O_3 with a p_{O3}=0.3174. This factor refers to the need for adaptation of buildings to climate change and alignment with sustainable and CE initiatives and policies. These factors show that the benefits generated in the environment are related to its positive contribution to policies in the CE, being a pioneering project and ambitious in terms of scope and impact, which is a benchmark for sustainability and circular economy policies in general.

It is worth highlighting the opportunity O_1 (p_{O1}=0.2030), the possibility offered by Level(s) to be included in certification and regulatory tools at different scales across Europe. This characteristic will contribute to the drive of its development since it can be assumed as its own in the current methodologies. Finally, with a local priority index p_{O2}=0.1912, there is the opportunity O_2, related to its capacity to act as a spearhead and reference point for sustainable initiatives. Being a pioneering and ambitious project in terms of scope and impact, Level(s) can be a benchmark for sustainability and circular economy policies. This character can encourage its initial impulse and development and, as well, its settlement as an example of a methodology of action. Society's awareness of sustainable development supports and legitimises the incorporation of Level(s) in concrete policies and regulations.

Threats (-). Figure 28d shows, in this case, somewhat different values when quantifying the threats to the development and implementation of Level(s), if not able to address them. The first and second are factors T_1, T_4 and T_3 (p_{T1}=0.2924, p_{T4}=0.2769, p_{T3}=0.2347) referring to the need to reach a consensus on the part of all countries of EC, either for their normative implementation or for the establishment of standard criteria for analysis. This outcome highlights concerns about the adoption of directives that may affect practices aimed at the development of climate change adapted sustainable building, within the context of the CE.

It may, therefore, be necessary to devise appropriate implementation strategies (although abrupt legislative changes, without any transitional rule, lead to confusion and discouragement of investment). It is also possible that the ability to attract investment in a sector that brings together so many disciplines will be hugely resented. As an example, consider the energy sector, where many policy decisions require years of maturation and implementation: major changes in policy orientation lead to inefficiencies that raise costs and harm competitiveness (Burke & Stephens, 2018; Xingang et al., 2011).

The threat that has reached a lower local priority index has been related to uncertainty in the data needed to carry out the analysis (T_2) (p_{T2}=0.1960). This highlights the impetuous need for strategies aimed at creating large databases at European level; these may even be useful for different fields of research, thus creating multiple synergies and feedback.

3.2.2. Determination of total priority indices

In order to determine the priority of the global factor in the first place, the weighting for each of the factors (strengths, weaknesses, opportunities and threats), W_S, W_W, W_O and W_T were calculated (based on the assessment obtained by the factors in the different categories). This was again done through the panel of experts, who was asked in the third round for a peer comparison of the four SWOT groups. This made it possible to obtain the weighting coefficients shown in Table 16. From the local priority indices and the weighting coefficients determined, the overall priority index was calculated for each of the relevant factors (q_i), obtaining the values given in Table 16 and Figure 29.

Figure 29 clearly shows how, according to expert opinion, the positive aspects of Level(s) (Strengths and Opportunities) prevail over the negative ones (Weaknesses and Threats). In Table 16, one can see, the first eight places in the order of hierarchy (as obtained from the global priority index) are occupied by Strengths and Opportunities; the factors that identify Weaknesses and Threats occupy the final eight positions of the list.

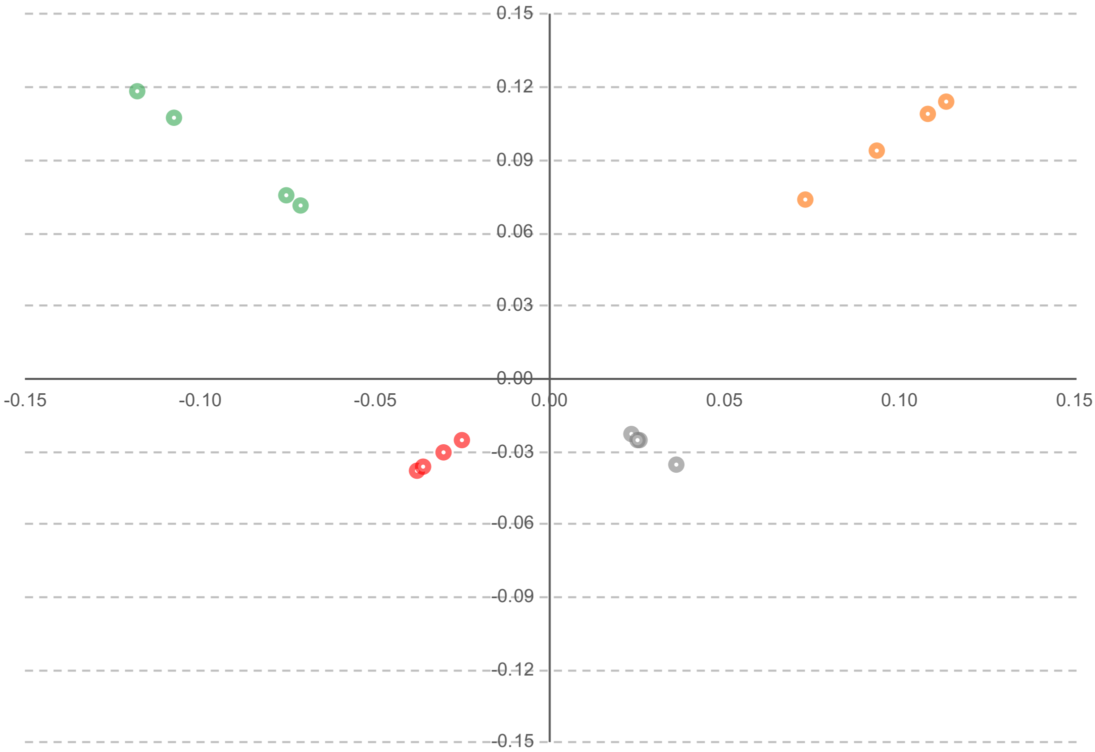


Figure 29. Overall priority of factors.

If the global priority indices corresponding to the different relevant factors are explicitly analysed, it is observed that the relevant factors with the highest overall value are the opportunity O_3, and the strengths S_2 and S_3, with values in the indices very similar (p_{O3}=0.1181, p_{S2}=0.1135, p_{S3}=0.1085). On the contrary, the least–valued aspects by the experts, globally, have been the weakness W_2 and W_3 with values of the overall priority index of 0.0230 and 0.0249 respectively. These factors refer to experts' concern about the inability to reach a consensus among all European countries on the criteria and factors of the Level(s) analysis, as well as the possible difficulty of its implementation by relying on databases that must also be common and duly verified. This implies the need for a systemic change in the sector approach, based on the CE so that all parts of the process are dependent on each other. This entails a change in the way we work, moving from modern individualism to a multidisciplinary approach, which can provoke resistance and lead to simplistic interpretations that limit, reduce, or nullify the tool's potential.

3.3. SWOT-AHP results. Sample quality

Finally, two procedures have been used to analyse the quality of the data obtained. On the one hand, the consistency of the judgements obtained from the series of paired comparisons was determined; on the other, the level of consensus, as determined by the CoV, was calculated in order to know the quality of the answers of the Delphi method.

As described, each phase of the study involved a different number of experts on the panel. Thus, the online survey conducted during the first phase successfully gathered the perspectives of 112 experts and a VoC=0.13. A reasonable degree of consensus was thus determined (without the need for an additional round). Interviews during the second phase were conducted with 88 experts, who were distributed more equitably among the groups that gave a VoC=0.24. Finally, during the third phase, a selection of the panel of experts of the second phase was contacted, and responses were obtained from 26 experts, with a VoC=0.27 being determined, as in the second phase, a reasonable degree of consensus, without the need for an additional round.

As can be seen in Figure 30, in the first round 13% and 4% of the respondents are experts in sustainable building and have worked with Level(s) respectively; given the heterogeneous nature of the panel, it is understood that these data are representative of the sample. In the second round, and after a selection process, 19% and 8% of respondents are experts in sustainable building or have worked with Level(s), respectively. Finally, in the last round, of the 26 experts surveyed, 57% and 21% of the respondents were experts in sustainable building or worked with Level(s) respectively; this value is considered high, given the novelty of this framework of indicators.

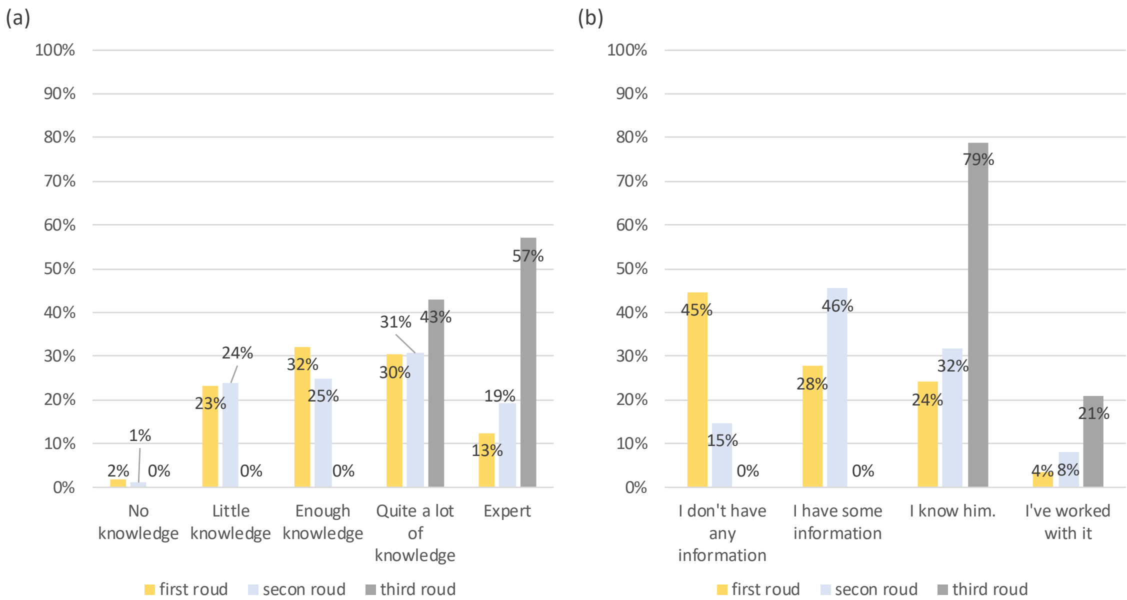


Figure 30. Experts' experience in sustainable building (a) and Level(s).

In order to determine the consistency of the judgments of paired comparisons, the values of the Consistency Ratio (CR) have been calculated, obtaining, CR= 0,001621896 for factors in the Strengths category; CR= 0.000100945 for Factors in the Weaknesses category; CR= 0.002252346 for Factors in Opportunity category; and CR= 0.005434977 for Factors in Threat category. In all cases, CR ≤ 0.10 these results thus ensured that the decision–making process was adequate.

3.4. Identification of strategies

The results obtained from the Level(s) SWOT + AHP analysis show that failure to adopt short term strategies could lead to loss of potential, uncertainty in results, and an inability to achieve a common framework of indicators. The identification of the strengths and weaknesses of this tool allows proposing four sets of specific measures, once all the strengths, weaknesses, opportunities and threats are known. Strategies, therefore, have been put in place to indicate the general objectives that Level(s) must achieve in the short and medium term (Figure 31). Finally, Figure 32 shows the main outcomes obtained.

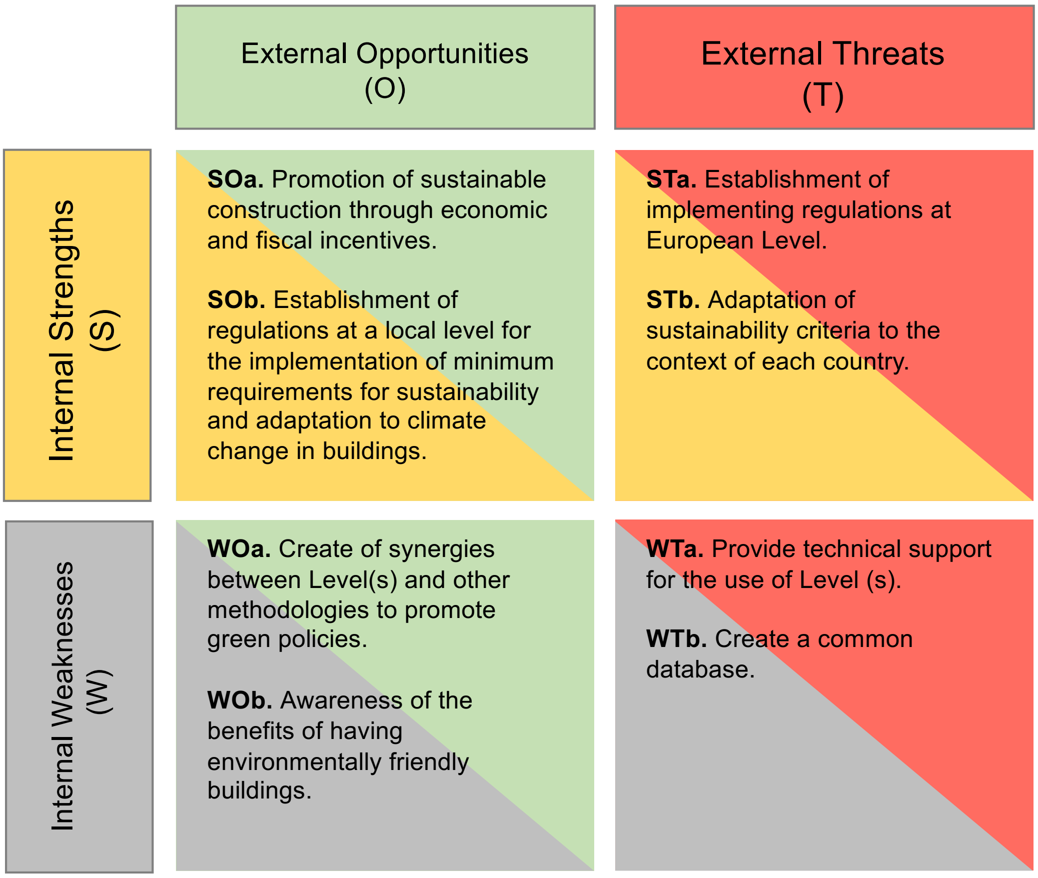


Figure 31. Identification of strategies.

3.4.1. Offensive Strategies

It is obtained by relating Strength3 + Opportunity1 (SOa). Promotion of sustainable construction through economic and fiscal incentives. Driving through fiscal incentives (taxes or fees) or economic incentives (funding or aid) public bodies can promote sustainability criteria in building at different stages of the building's life cycle.

It is obtained by relating Strength4 + Opportunity3 (SOb). Establishment of regulations at a local level for the implementation of minimum requirements for sustainability and adaptation to climate change in buildings. Employing local regulations and standards the different public bodies can demand a minimum of sustainability and adaptation to climate change in the building.

3.4.2. Defensive Strategies

It is obtained by relating Strength1 + Threat1 (STa). Establishment of implementing regulations at European Level. Launch by the EUof regulations on the application and regularisation of sustainability criteria.

It is obtained by relating Strength2 + Threat3 (STb). Adaptation of sustainability criteria to the context of each country. Being a common reference language for all Europe, a consensus can be reached among all European countries, allowing each country to adopt the criteria to its constructive and socio-economic conditions, without losing the character of a common language.

3.4.3. Adaptive Strategies

It is obtained by relating Weakness3 + Opportunity4 (WOa). Create of synergies between Level(s) and other methodologies to promote green policies. Through synergies between Level(s) and other methodologies, already established, initiatives and policies of the circular economy and sustainable can be promoted.

It is obtained by relating Weakness4 + Opportunity2 (WOb). Awareness of the benefits of having environmentally friendly buildings. Raise awareness of all actors involved in the construction sector of the need for environmentally friendly buildings.

3.4.4. Survival Strategies

It is obtained by relating Weakness4 + Threat4 (WTa). Provide technical support for the use of Level(s). Provide courses, workshops and all the necessary material for the correct management of the Level(s) by the competent administration.

It is obtained by relating Weakness2 + Threat2 (WTb). Create a common database. Create a common database to facilitate the homogeneity of criteria in all countries of the European Union.

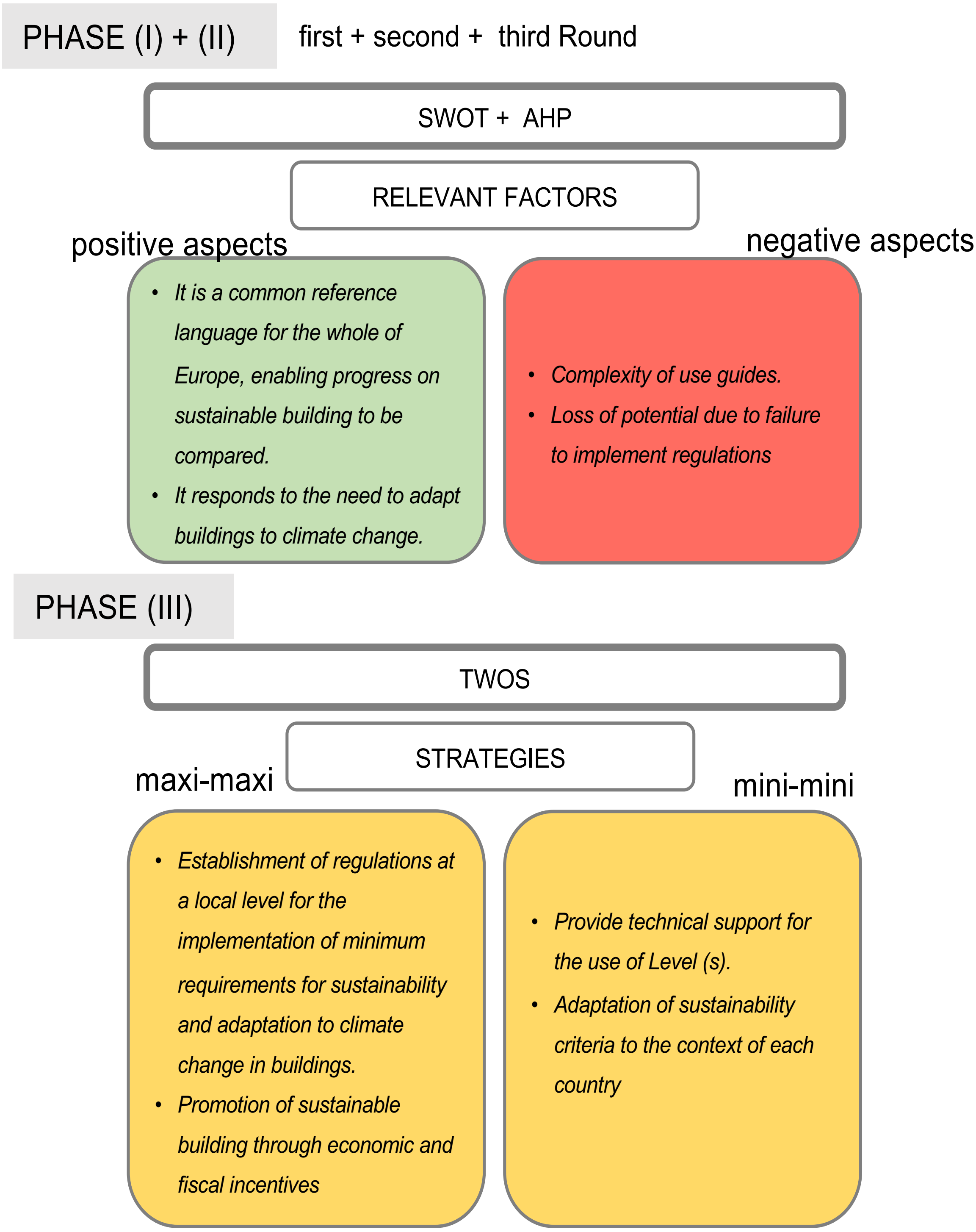


Figure 32. Summary of outcomes.

4. Conclusions

Level(s) aims to unite the whole sector value chain around a common European language for better building performance. It looks at the full lifecycle of buildings to address their huge potential for emissions reductions, efficient and circular resource flows, and supporting the health and wellbeing of those they are built to serve.

The implementation of the combination of the SWOT + AHP analysis has made it possible to identify and quantify strengths and weaknesses that facilitate the development of Level(s) in Spain and, further, the establishment of strategies to facilitate their implementation. The methodology used in this study, as well as the results obtained, can be extrapolated to countries in the EU with a similar development in terms of sustainable construction, especially those in the Mediterranean arc.

The analysis of the values of the global priority indices clearly shows how the factors relating to the strengths and opportunities of Level(s) outweigh their weaknesses and threats. The results obtained, therefore, are conclusive in terms of the experts' positive assessment of the tool.

From its design, the most valued aspects of the tool have been (i) It responds to the need to adapt buildings to climate change and (ii) the fact that Level(s) is a common and reference language for the whole of Europe, that allows us to compare progress in sustainable building. However, several barriers have also been identified which may affect its smooth development. These include its complexity of use and its lack of self-sufficiency (and hence the dependence on other procedures/databases, with the different assessment criteria this may imply).

On the other hand, the experts think that the use of Level(s) will generate a set of benefits in the environment related to its positive contribution to CE-related policies, given its pioneering and ambitious nature in terms of scope and impact. This makes it a benchmark for sustainability and circular economy policies in general. Similarly, its ability to be included in certification and regulatory tools at different scales across Europe will contribute to the drive of its development, as it can be taken up on its own. However, the vast potential of Level(s) may be compromised if it is not implemented in regulations, as there is a risk of losing the tool's benefits if it is extended as a frame of reference.

Therefore, it can be concluded that the experts recommend that the EC develop a set of strategies in the short and medium-term to publicise the Level(s) and encourage their application. To this end, it is necessary to maximise the strengths and opportunities identified. The need to establish economic and fiscal incentives to promote sustainability criteria is highlighted, and regulations governing the requirement of sustainability criteria and adaptation to climate change in buildings. Consequently, it is essential to identify the effect of climate change on buildings in order to be able to regulate, design and evaluate buildings that not only mitigate but also adapt to climate change, especially in urban areas.

CHAPTER 4

Effects of climate change on building design. A case study in Spain[4]

[4] The results shown in this chapter were presented in: C. Díaz-López, J. Jódar, K. Verichev, M. L. Rodríguez, M. Carpio, M. Zamorano. Dynamics of changes in climate zones and building energy demand. A case study in Spain. Applied Science. 11(9), 4261 (2021). https://doi.org/10.3390/app11094261

The results shown in this chapter are under review in: C. Díaz-López, K. Verichev, J. A. Holgado-Terriza, M. Zamorano. Evolution of climate zones for building in Spain in the face of climate change. Sustainability Cities and Society.

1. Introduction

In the current context of climate change, and in light of the results of the previous chapter, the need to identify the effect that climate change has and will have on the correct design of sustainable buildings is highlighted. It is essential in order to lay the foundations for standards and regulations that implement the requirement of minimum climate change adaptation criteria. Furthermore, the study of the effect of the climate context on a building is fundamental for the correct assessment of sustainability throughout its life cycle; this being a fundamental issue for the development of SBAMs.

According to the 5th assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), compared to values from 1850 to 1900, the global land surface temperature increased by 0.85° C between 1880-2012 and 0.78° C between 2003-2012 (IPCC, 2014). The AR5 is the primary quantitative parameter describing climate change is the total radiative forcing (RF) of the climate system. RF shows a change in the climate system's energy balance due to anthropogenic activity since 1750 and GHG emissions. In 2011, the RF value was 2.29 W/m^2.

This report also presents a set of four possible scenarios of climate change, called Representative Concentration Pathways (RCP) (IPCC, 2014). These scenarios are characterised by the approximate calculation that gives the RF in the year 2100, with respect to the year 1750 taking into consideration different trajectories for emissions of long-lived greenhouse gases (LLGHGs) and short-lived air pollutants, the corresponding concentration levels and land use (Chuwah et al., 2013). In the following, a description is given of the two scenarios within which the present study is realised. These scenarios were selected due to their wide application in other studies related to climate change, building EC and climate zones for buildings (Verichev et al., 2020).

- **RCP 4.5.** An intermediate stabilisation pathway in which RF is stabilised at approximately 4.5 W/m^2 after 2100. It will be necessary to limit emissions through increased use of electricity, lower-emission energies, CO_2 capture technologies and geological storage. The area of forests is also expected to increase for this scenario, compared to the current state. Furthermore, CO_2 emissions from energy and industrial sources are expected to increase until 2040 and then decrease to the prescribed atmospheric CO_2 concentration of 538 ppm in 2100. At the same time, by 2081–2100, the global mean surface temperature will increase by 1.8°C (likely range 1.1°C to 2.6°C) compared to the 1986–2005 climate period (IPCC, 2013; Thomson et al., 2011).

- **RCP 8.5.** During the 21st century, RF will grow steadily and reach 8.5 W/m^2 in 2100. Very high GHG emissions characterise the scenario. RCP 8.5 combines the assumptions of a steady increase in the global population, a moderate rate of technological change, and energy intensity improvements. In the long term, this leads to high energy demand and GHG emissions in the absence of a climate change policy. The prescribed CO_2 concentration is 936 ppm in 2100. At the same time, by 2081–2100, the global mean surface temperature will increase by 3.7°C (likely range 2.6°C to 4.8°C) compared to 1986–2005 (IPCC, 2014).

These changing environmental effects can have a substantial impact on the behaviour and performance of a building throughout its life cycle if they are not taken into account at the design stage (de Wilde & Coley, 2012). In this sense, if buildings are designed without considering climatic dynamics, within a short period, they will be unable to provide the adequate thermal comfort for which they have been designed, incurring an extra cost in terms of EC, and may cause the deterioration of building frames and structural components (Brown et al., 2016; Grøntoft, 2011; Nik et al., 2015; Troup et al., 2019).

In this context, the EUpresented the Directive (EU) 2018/844 (European Union, 2018) of the European Parliament and of the Council of May 30, 2018, on energy efficiency, which, together with the European Green Deal, will adopt a new, more ambitious EU strategy for the adaptation to climate change. Strengthening the efforts on climate-proofing, resilience of the building, prevention, and preparedness is crucial, so work on climate adaptation should continue to influence public and private investments (Mulvaney, 2019). In this regard, EU countries should establish long-term strategies to support the renovation of their buildings, transforming them into almost nZEB by 2050 (European Commission, 2011). These new regulations require sustainable and resilient buildings, which integrate constructive solutions and green technologies that not only mitigate but also adapt to the different climate scenarios to come, given the recognition that mitigation alone is insufficient to prevent the expected impacts (Biesbroek et al., 2010). Therefore, an understanding of changing climate impacts would help regulators and designers to develop better investment strategies to ensure nearly zero-consumption buildings throughout their life cycle.

In order to mitigate and adapt to these climate effects, the EC presented Directive (EU) 2018/844 (European Commission, 2018) of the European Parliament and the Council of 30 May 2018 on energy efficiency, which, together with the European Green Deal (Mulvaney, 2019), will adopt a new and more ambitious EU strategy on adaptation to climate change. In this context, many countries have developed regulations based on climate zone classification, a beneficial method to design buildings with lower energy consumption (Board, 2015; Council & Officials, 2000; Heating & Refrigerating, 2000), and high thermal confort (Rakoto-Joseph et al., 2009). his method is based on analysing large amounts of meteorological, environmental and social data to contribute to the search for climate models that absorb all of the above (Walsh et al., 2017).

The number of climate zones (CZ) depends on each country, the thresholds set, and the methodology used. For example, Spain, in the Technical Building Code (CTE in spanish) (Spain, 2019), establishes 15 CZs (α3, A2, A3, A4, B2, B3, B4, C1, C2, C3, C4, D1, D2, D3, E1) identified by a letter corresponding to the climatic severity in winter (α, A, B, C, D, and E) and a number (1, 2, 3 and 4) corresponding to the summer values. Portugal establishes nine climate zones (I1−V1, I1−V2, I1−V3, I2−V1, I2−V2, I2−V3, I3−V1, I3−V2, I3−V3) from the different combinations of winter letters (V1, V2 and V3) and summer letters (I1, I2 and I3) (Ferreira et al., 2009); France establishes eight CZs (H1a, H1b, H1c, H2a, H2b, H2c, H2d, H3), taking into account winter temperatures (H1, H2 and H3) and summer temperatures (a, b, c and d) (France, 2011). In any case, the climatic zonings used in different countries are based on the climatic series existing at the time of their formulation, and therefore do not allow the design of building parks capable of adapting to climatic dynamism (Carpio et al., 2015).

Consequently, it is essential to design and construct buildings capable of assuming the climatic dynamics throughout their life cycle. As concluded in previous chapters, the experts consulted have highlighted in their assessment of Level(s) the lack of data on climate dynamism and its impact on buildings, and therefore the need to adapt buildings to climate change. It has resulted in the proposal of strategies to establish local standard regulations that allow for the demand of sustainability criteria and adaptation to climate change in buildings, in line with the most recent studies on the impact of climate dynamism.

Therefore, knowledge of the climatic reality will guarantee the development of a building stock that is certainly sustainable and resilient. For this reason, the main objective of this chapter has been to analyse the dynamics of changes in CZs, their effect on the energy demand of buildings and the tools used today to design buildings per the required standards. Spain has been selected as the study area because of its climatic variety, which will allow the methodology applied, the results and the conclusions obtained to be used as a reference in other regions. Furthermore, in this country, there is low investment in sustainable building, with the construction sector being one of its primary energy consumers, which translates into one of the highest rates of consumption per Gross Domestic Product (GDP) in the European Union (Lastra-Bravo et al., 2013), which highlights the urgent need to take measures to solve this problem.

1.1. Background and related works

The literature review yields numerous studies that place particular emphasis on climate dynamism in the building design phase, without which the estimated energy demand could triple (Brown et al., 2016; Grøntoft, 2011; Nik et al., 2015; Troup et al., 2019). In this way, to assess changes in the heating and cooling EC of residential buildings, different techniques have been used to approximate future climatic conditions. Thus, in the work of Gaterell and McEvoy (Gaterell & McEvoy, 2005) it is assumed that the Milan weather file can be used to represent the UK climate in 2050 under a low emissions climate scenario and that of Rome for the UK climate by 2050 under a high emissions climate scenario.

Christenson et al. (Christenson et al., 2006) analysed how the impact of global warming increases the cooling energy demand of buildings. In the study by de Rosa et al. (De Rosa et al., 2014), a simplified building dynamic model, based on the electrical analogy, has been developed and implemented in the MATLAB/Simulink environment, in order to perform several analyses on the heating and cooling energy demand in a wide range of climatic conditions. Verichev et al. (Verichev et al., 2020) analyse the effects of climate change on variations in CZs and the heating energy consumption of residential buildings in southern Chile.

Studies have been conducted in which the effects of climate change on the heating/cooling energy consumption have been analysed (Kendrick et al., 2012) on the basis of indoor temperature and thermal comfort (Barclay et al., 2012) and building adaptation methods in climate change conditions (R. Gupta & Gregg, 2012), based on scenarios developed by local meteorological institutes such as the United Kingdom Climate Impacts Program (UKCIP), the Royal Netherlands Meteorological Institute in the Netherlands (Hamdy et al., 2017), the Environment Agency of Abu Dhabi and the Ministry of Energy in the United Arab Emirates (Radhi, 2009), and the National Institute for Environmental Studies and Agency for Marine-Earth Science and Technology of Japan (Arima et al., 2016).

2. Materials and methods

An update of CZs of the CTE (Spain, 2019) of 7967 localities of peninsular Spain has been carried out, under two of the four scenarios called Representative Concentration Pathways (RCPs) (RCP2.6, RCP4.5, RCP6.0 and RCP8.5), specifically RCP 4.5 and RCP 8.5 scenarios, to achieve the objective of this study. These scenarios are characterised by their approximate calculation of the total Radiative Forcing (RFtot) in the year 2100, relative to 1750 (Verichev et al., 2020). Each scenario describes a different trajectory for long-lived greenhouse gas emissions (LLGHGs) and short–lived air pollutants, the corresponding concentration levels, land use, and radiative forcing (Chuwah et al., 2013).

Besides, to know the effect of this dynamic of changes in the energy consumption of buildings, a standard home has been taken as a reference, and the evolution of its energy demand has been analyzed. The description of the bases for the definition of CZs of the CTE and its methodology are described below.

2.1. Basis for the definition of CTE climate zones

In Spain, the CTE and its DB-HE (Basic Document on Energy Saving of the Technical Building Code) (Spain, 2019) establishes a methodology that allows the definition of CZs for buildings. This methodology is based on the concept of climatic severity index (CSI), a unique number on a dimensionless scale that is specific for each geographical location (Salmerón et al., 2013) and that allows differentiating between climatic severity index for summer (SCS) and winter (WCS).

The WCS and SCS indices are obtained by applying Equation 6 and 7 (Spain, 2019) respectively, where, $HDD20_{oct\text{-}may}$ is the sum of winter degree–days in 20°C bases for the months ranging from October to May, calculated through the hourly method; $CDD20_{jun\text{-}sep}$ is the sum of summer degree-days in 20°C bases for the months ranging from June to September, calculated through the hourly method; a, b, c, d and e are the regression coefficients whose values are a=3.546 x 10^{-4}, b= -4.043 x 10^{-1}, c=8.394 x 10^{-8}, d= -7.325 x 10^{-2}, e= -1.137 x 10^{-1}, in the case of WCS, and a=2.990 x 10^{-3}, b= -1.1597 x 10^{-7} , c= -1.713 x 10^{-1}, in the case of SCS ; n is the sum of sunshine duration hours in the period from October to May; and N is the sum of maximum possible of sunshine duration hours for the months from October to May.

$$WCS = a \cdot HDD20_{oct-may} + b \cdot \frac{n}{N} + c \cdot HDD20_{oct-may}{}^{2} + d \cdot \left(\frac{n}{N}\right)^{2} + e \quad (6)$$

$$SCS = a \cdot CDD20_{jun-sep} + b \cdot CDD20_{jun-sep}{}^{2} + c \ (7)$$

Each of the six winter CZs defined in the DB−HE is assigned a letter (α, A, B, C, D and E) corresponding to the WCS interval indicated in Table 1, with the CZ having the warmest winter and E the coldest. By the four summer CZs defined in the DB−HE and identified with a number (1, 2, 3 and 4), these are determined according to the SCS. Besides, it corresponds to the interval indicated in Table 17, being 1 the climate zone with the least warm summer and 4 the warmest (Spain, 2019). Finally, the combination of letter and number given in Table 17 is the one that generates the building CZ code for any city or geographical location. According to the provisions of the DB−HE document of CTE in Spain, there are 12 possible combinations and, as a result, CZs (A3, A4, B3, B4, C1, C2, C3, C4, D1, D2, D3 and E1).

Table 17. Intervals for climate zoning.

intervals for winter zoning					
α	**A**	**B**	**C**	**D**	**E**
WCS ≤ 0	0 < WCS ≤ 0.23	0.23 < WCS ≤ 0.5	0.5 < WCS ≤ 0.93	0.93 < WCS ≤ 1.51	WCS > 1. 51

intervals for summer zoning			
1	**2**	**3**	**4**
SCS≤ 0.5	0.5 < SCS ≤ 0.83	0.83 < SCS ≤ 1.38	SCS > 1.38

2.2. Data processing

The PI platform from OSIsoft (OSIsoft, 2020) was used for the development of the work. It is used for persistent data storage and processing because it facilitates the management of vast amounts of data and events in real time. In order to audit the calculations performed in this research, according to the proposed hypothesis, a reliable and adaptable database was designed and built based on the meteorological data provided by AEMET. For the creation of this database, raw data points of two or three years of measurement were organised on the basis of the meteorological stations using parent–child relationships according to their location and the city where they are located. The database design was developed in three stages: (i) definition of a database schema in PI (definition of assets and attributes); (ii) design of the data import process, and finally; (iii) definition of the analysis and data export procedure. In the last stage, the calculations explained later were carried out, as well as the analysis obtained with respect to the various scenarios proposed.

2.3. Methodology

The methodology used to achieve the objectives of this chapter consists of four phases, which are described in the following sections: (i) determination of climate severity indices; (ii) determination of the dynamics of changes in climate severity indices; (iii) proposal for updating CZs for peninsular Spain; and (iv) evaluation of the dynamics of changes in energy demand in housing.

2.3.1. Determination of climate severity indices

From among the almost 800 weather stations located by the State Meteorological Agency (AEMET) in peninsular Spain (AEMET, 2020), whose data can be provided for research, a total of 77 were selected (Figure 33). Considering their proximity to urban centres and a homogeneous distribution based on these centres' population, they were also sought with a minimum measurement period of 3 years, between 2015–2018, and which had hourly temperature measurement data available. As for the data relating to sunshine duration hours, 55 of them were able to provide them; in the case of the remaining 22 stations, the data from the geographically closest station that had them was used.

At each of these stations, the WCS and SCS indices were calculated using as a basis for calculation equations 6 and 7 of the CTE (Spain, 2019) described in the previous section. In the case of equation 6, the values of N, for each geographical location of stations, were calculated with the application "NOAA solar calculations year" (NOAA ESRL GMD, 2019) by the NOAA Earth System Research Laboratory (ESRL) Global Monitoring Division.

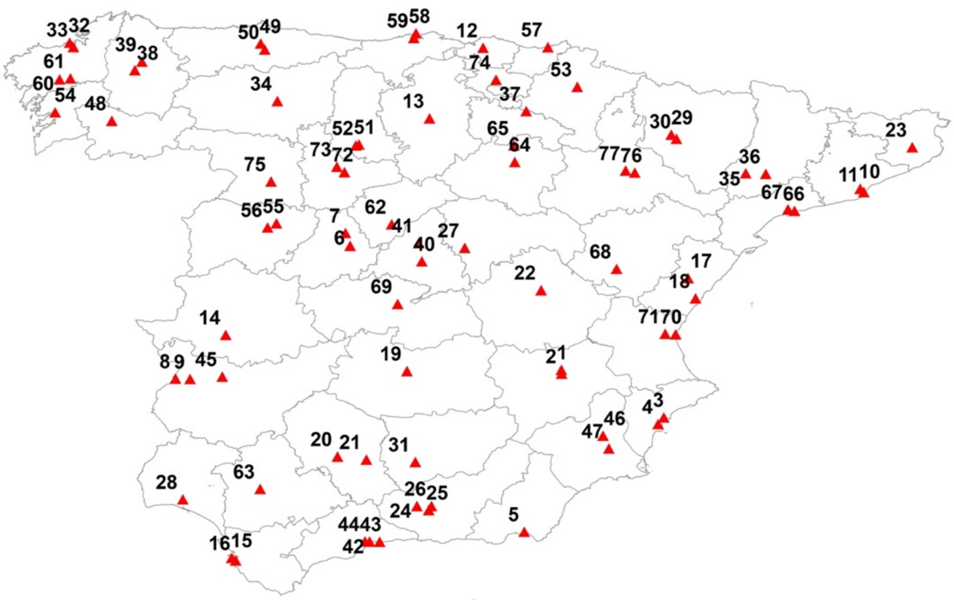


Figure 33. Geographical location of the reference meteorological stations of AEMET

2.3.2. Determining the dynamics of changes in climate severity indices

The calculation of the changes for the WCS and SCS indices of each of the stations was carried out using the Climate Change Adaptation Platform (AdapteCCa, 2015) which contains the results of daily minimum and maximum temperature projections for the RCP4.5 and RCP8.5 scenarios from a total of 16 climatological models.

Based on the projection data and current hourly temperature measurement data from AEMET, for each of the 77 meteorological stations, firstly, the difference values (or deltas) of the monthly average temperature between the baseline climate period (2018) and the two future periods (2055 and 2085) were calculated. Then, the hourly data from the AEMET stations were modified based on the monthly temperature deltas obtained. The modification of hourly temperature data has been carried out according to methodologies already presented in other scientific works (Belcher et al., 2005; Chan, 2011; Jiang et al., 2018), based on which it is possible to apply the "a shift" algorithm to modify baseline climate data, to modify hourly baseline climate temperature values by adding the projected monthly average difference for future years.

For this purpose, Equations 8 and 9 (Spain, 2019) have been used to calculate HDD and CDD, respectively, in the future; where $\mathrm{HDD}_{\mathrm{d,Y}}$ and $\mathrm{CDD}_{\mathrm{d,Y}}$–are daily values of HDD and CDD in the future; $\mathrm{T}_{\mathrm{i,2018}}$–temperature of measurements in i-hour of the day in the year 2018; $\Delta\mathrm{T}^{\mathrm{j}}_{\mathrm{Y-2018}}$–delta of monthly temperatures in j-month between years in future (Y = 2055 and 2085) and baseline climate.

$$HDD_{d,Y} = \left[\sum_{i=1}^{24}\left(T_b - (T_{i,2018} + \Delta T^{j}_{Y-2018})\right)^{+}\right]\frac{1}{24} \quad (8)$$

$$CDD_{d,Y} = \left[\sum_{i=1}^{24}\left(\left(T_{i,2018} + \Delta T^{j}_{Y-2018}\right) - T_b)\right)^{+}\right]\frac{1}{24} \quad (9)$$

Based on the modified HDD and CDD results for the future, the WCS (Equation 8) and SCS (Equation 9) values for 2055 and 2085 were recalculated to account only for temperature changes without estimating changes in sunshine duration hours for the WCS index. This simplification was possible because the temperature in the climate models for the future already takes into account changes in atmospheric radiative conditions. Finally, the WCS and SCS indices were calculated

2.3.3. Proposed update of climate zones for peninsular Spain

The CZ classification for the 7967 peninsular Spanish localities of our research is based on determining their WCS and SCS indices.

Firstly, the computation of the WCS and SCS indices at the 77 weather stations as described above is carried out. It can be done by applying the formulae given in that section because the values of temperature and sunshine duration hours required in the corresponding equations are available for those locations. These values are not available for the 7967 Localities, and, as a consequence, their WCS and SCS indices cannot be calculated as done for the 77 weather stations. Their determination is then obtained by approximation, using an interpolation method based on radial basis functions (RBF). Given the geographical size of the cities containing two or more reference stations, a weighted average of the SCS and WCS indices of each of the meteorological stations corresponding to each city was made to obtain the SCS and WCS indices of the 49 cities.

For a given set of data (measurements and locations at which these measurements were obtained), the approximation procedure tries to determine a function (approximating function) that is a good fit for the given data. In the approximation process using interpolation, this good fit is achieved by imposing that the approximating function's outputs exactly match the given measurements at the corresponding locations. Besides, information on the studied problem can also be deduced at locations different from where the measurements were obtained (Burden et al., 2016).

Approximation, and in particular interpolation employing RBF, has found significant applications in science, engineering, economics, biology, and medicine, among others. In our case, the determination of the WCS and SCS indices at the 7967 localities from the WCS and SCS indices calculated at the 77 weather stations was obtained by using an approximant expressed as a finite linear combination of a particular radial basis function and its translations (it is important to emphasize that the selected 77 weather stations are well distributed throughout peninsular Spain). To make this approximation, the inverse multiquadric function is given by the expression $\phi(r) = \frac{1}{\sqrt{1+(\varepsilon r)^2}}$, $r \geq 0$, was chosen as the basis function, but there are other possibilities. A wide range of radial basis functions can be found in the literature (Buhmann, 2003). The parameter $\varepsilon \geq 0$ that appears in the above expression is a shape parameter.

Let us illustrate the determination of the climatic severity indices more precisely. For the case of the WCS index, an interpolant function s(x,y,z) given by the expression:

$$s(x, y, z) = \sum_{i=1}^{77} a_i \phi(\| (x, y, z) - (x_i, y_i, z_i) \|)$$

is considered, where (x_i, y_i, z_i) R^3, i = 1, …, 77, represent the latitude, longitude and altitude coordinates at each of the 77 weather stations, ‖.‖ is the Euclidean norm on R^3, φ : [0, ∞) → R is the basis function and a_i, i = 1, …, 77, constitutes a set of real coefficients to be determined.

These coefficients are obtained by imposing that the output provided by the interpolant function s at each of the weather stations is the corresponding WCS index, which is known. Once the coefficients are calculated, the interpolant function s is therefore determined. The evaluation of s at any value (*x, y, z*) $\in$ R^3 corresponding to the latitude, longitude and altitude coordinates at any peninsular Spanish location provides the searched approximation for the unknown WCS index at that location. The SCS case would be analogous.

This is the procedure followed for the 2015–2018 period. The corresponding one for the years 2055 and 2085 is utterly similar except that, for the starting stage, the WCS and SCS indices at the 77 weather stations, both for the RCP 4.5 and RCP 8.5 contexts, need to be recalculated, as described in Section 2.2.2.

Once the WCS and SCS indices are obtained at each of the 7967 localities, they can be classified inside the corresponding CZ. Remarkably, the main advantage of the interpolation method previously exhibited is that it provides a continuous function to compute the climatic severity indices at any location. Consequently, it could make possible a numerical climatic classification at any municipality instead of the more rigid one described by zones.

2.3.4. Assessment of the dynamics of changes in energy demand in dwellings.

Once the WCS and SCS indices have been calculated for the periods 2015–2018, 2055 and 2085, an analysis of the dynamics of changes in energy demand is carried out for the RCP 4.5 and RCP 8.5 scenarios in the 77 locations of the meteorological stations selected for the study. The city of Madrid, has been taken as a geographical reference point, to which, according to the CTE, the values WCS=1.0 and SCS=1.0 (Spain, 2019); correspond; consequently, by multiplying the value of the energy demand of a dwelling located in Madrid by the value of the WCS (or SCS) index of any geographical location, it is possible to estimate the demand of that dwelling in that place.

For this analysis, a typical building of a six–storey multi–family block of flats, used in the work of López-Ochoa et al. (López-Ochoa et al., 2017) was considered. The block consists of a ground floor and five storeys. Its base measures 22 by 22 m, which is equivalent to an area of 484 m^2. The height of each floor is 3 m. The main facade faces north. Each of the five floors has 4 types of flats: Apartment A has 3 bedrooms and a size of 100.05 m^2; Apartment B has 3 bedrooms and a size of 101.93 m; Apartment C has 4 bedrooms and a size of 137.64 m^2; and Apartment D has 3 bedrooms and a size of 103.69 m^2.

The building's thermal transmittances are similar to the limit values set in CTE–DB–HE1 2009, fulfilling the requirements of CTE–DB–HE 2009 (Spain, 2009). The energy demand for heating this house in Madrid is 42.74 kWh/m^2 year and for cooling is 14.09 kWh/m^2 year (López-Ochoa et al., 2017).

3. Results and discussions

After applying the previous section's methodological steps, the results shown in Figures 34–42 and Tables 17–20 were obtained, which are analysed and discussed below.

3.1. Determination of climate severity indices

Figure 34 shows the values of the new CSs at the location of the 77 meteorological stations, according to the CTE calculation methodology, and taking into account the climatic conditions of the period 2015–2018.

It is observed that the WCS index values range between -0.06 and 1.87, determined for the coastal province of Malaga (station #43) and Soria (station #65), respectively. The three negative WCS values recorded, one case with a value of 0, or positive but shallow values, below 0.4, have occurred in regions with mild winters; this is the case of the station above #43, located in Málaga, #15 and #42, located in Cádiz and Málaga respectively, or stations #4 (Alicante), #11 (Barcelona), #16 (Cádiz), #18

(Castellón), #28 (Huelva), #44 (Málaga), #66 (Tarragona), and #70 (Valencia), among others, all of the coastal areas in the south of the peninsula or the Mediterranean area. In these cases, a good design of the building's constructive solutions will allow the indoor comfort temperature to be reached without implementing active heating systems. On the contrary, the higher the WSC value, the lower the winter temperatures in these regions, which leads to higher heating energy demands. This is the case of stations #6 and #7 located in Avila, #13 in Burgos, #52 in Palencia, #56 in Zamora, and #64 and #65 in Soria, all of them with WSC values higher than 1.35 and located in the north of the peninsula, in provinces with shallow temperatures.

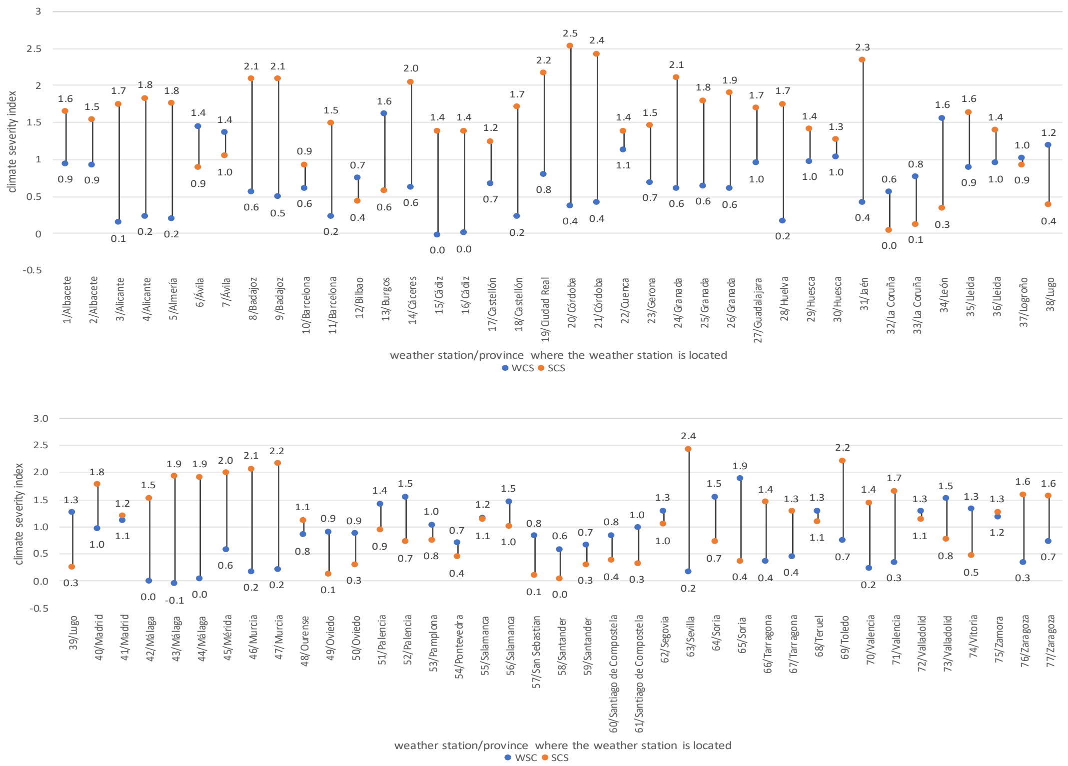


Figure 34. Calculated indices of WCS and SCS for the period 2015–2018.

In the case of the SCS, values reaching the minimum in the coastal province of La Coruña (station #32), with 0.04, and the maximum in the inland province of Cordoba (station #20), with 2.52, are observed. The lowest SCS values occur in regions with cool summer temperatures; this is the case of stations #32, #33, #60 and #61 located in La Coruña, #34 in León, #49 and #50 in Asturias, #57 in Gipuzkoa, #58 and #59 in Cantabria, among others, all of them in the north of the peninsula and with SCS values below 0.4. In these regions, with a good design of the building's constructive solutions, the indoor comfort temperature can be reached without implementing active cooling systems. However, the higher the SCS value, the higher the summer temperatures in these regions, which leads to higher cooling energy demands. It is the case of stations located in the peninsula's interior, with SCS values higher than 2, such as #8 and #9 in Badajoz, #14 in Cáceres, #19 Ciudad Real, or #20 and #21 in Córdoba, among others.

The stations located in the inland provinces of Madrid (#40, #41), Salamanca (#55, #56) or Segovia (#62) stand out, with WCS and SCS values higher than 1. These conditions are found in places with a Mediterranean climate far from the sea, with long and cold winters, with temperatures that can drop below 0ºC, with numerous frosts occurring at night. In contrast, summers are pretty hot and dry, with a temperature range of 18.5 °C, and temperatures often exceed 30 °C. In these regions, the energy demand is considerably higher than in coastal areas, both in summer and winter, where the need for passive strategies to reduce energy consumption is essential. Thus, building solutions with high thermal inertia could be an effective mechanism to achieve thermal comfort (Avendaño-Vera et al., 2020).

Finally, comparing the climate severity values of the different station locations in a province shows significant temperature contrasts between the urban and metropolitan regions, for example, the case in Barcelona, where station #11, located in the city centre and close to the seacoast, resulted in climatic severities of WCS=0.23 and SCS=1.48, while station #10, located outside the city centre, showed significantly different values (with WCS=0.61 and SCS=0.92).

The same is true for the stations in Valladolid, where station #72, located in the city centre, resulted in climatic severities of WCS=1.27 and SCS=1.12 while station #73, located outside the city centre, showed considerably different values (with WCS=1.51 and SCS=0.76). These results highlight the urban heat island effect, a phenomenon of thermal origin that occurs in urban areas and consists of a different temperature, which tends to be higher, especially at night, in the centre of cities due to massive building (Parker, 2020).

3.2. Determination of the dynamics of changes in climate severity indices

Figures 35 and 36 show the results obtained from calculating the WCS and SCS indices for the years 2055 and 2085, under the RCP 4.5 and RCP 8.5 climate change scenarios at the 77 reference stations.

Figure 35. Calculated indices of winter (WCS) and summer (SCS) climate severity for the RCP 4.5.

Figure 36. Calculated indices of WCS and SCS climate for the RCP 8.5.

For the RCP 8.5 scenario (Figure 36), a more drastic change in WCS and SCS values is observed than in the previous scenario. Thus, the WCS index values for 2055 range from -0.1 to 1.4 and decrease until 2085, with values ranging from -0.1 to 1.1. In SCS, a progressive increase is observed until 2055, to increase dramatically until 2085, with values ranging between 0.2 and 3 and 0.5 and 3.7. It reflects by the end of the century and increases in cooling energy demands and an almost total decrease in heating energy demands in most cities of the reference seasons.

3.3. Proposed update of climate zones for peninsular Spain

Based on the climate severities calculated from the 77 meteorological stations for 2015-2018 and the RCP 4.5 and 8.5 scenarios, the climate severities for the period 2015–2018 and the years 2055 and 2085 for 7967 localities in peninsular Spain have been obtained using approximation techniques. Besides, for those 49 cities, which include or are close to 2 or more reference stations, their WCS and SCS indices have been obtained from the weighted average of the WCS and SCS indices of the cited stations. Based on Table 17, the CZs of the 7697 localities have been identified. The results are described in Figure 37–42 and Tables 18 and 19 below.

3.3.1. Climate severities for 2015–2018 and the periods 2055 and 2085 of the RCP 4.5 and 8.5 scenarios for 7967 locations in peninsular Spain

Figure 37 shows the average WCS and SCS values for 2015–2018 and 2055 and 2085 for RCP 4.5 and 8.5. Comparing the values obtained for the WCS indices with those for the 2015-2018 range (Figure 37) shows that, for the RCP 4.5 scenario, the average value decreases considerably from 0.96 in 2015-2018 to 0.57 and 0.56 in 2055 and 2085, respectively. It is because emissions in this scenario peak around 2040 and then stabilise. In the RCP 8.5 scenario, the decrease is more significant, with average values of 0.43 and 0.28 for 2055 and 2085, respectively, due to the more abrupt character of this scenario, where the most significant changes are located to the end of the 21st century. For both scenarios, there is a significant softening of winter temperatures. For the SCS indices, the comparison with the values obtained in the 2015-2018 interval (Figure 30b) shows that, for the RCP 4.5 scenario, the average value increases from 1.15 in 2015-2018 to 1.43 in 2055; it then stabilises until 2085 with 1.45. In the RCP 8.5 scenario for 2055, compared to 2015-2018, a slight increase is observed with 1.43 before rising sharply to 1.93 by 2085. The most pessimistic climate change projection will lead to more noticeable temperature changes, with sweltering summers. Finally, it should be noted that it is not possible to compare these indices with current regulations since the CTE does not provide exact values, which leads to problems in the field of energy efficiency research and adaptation to climate change in buildings in Spain.

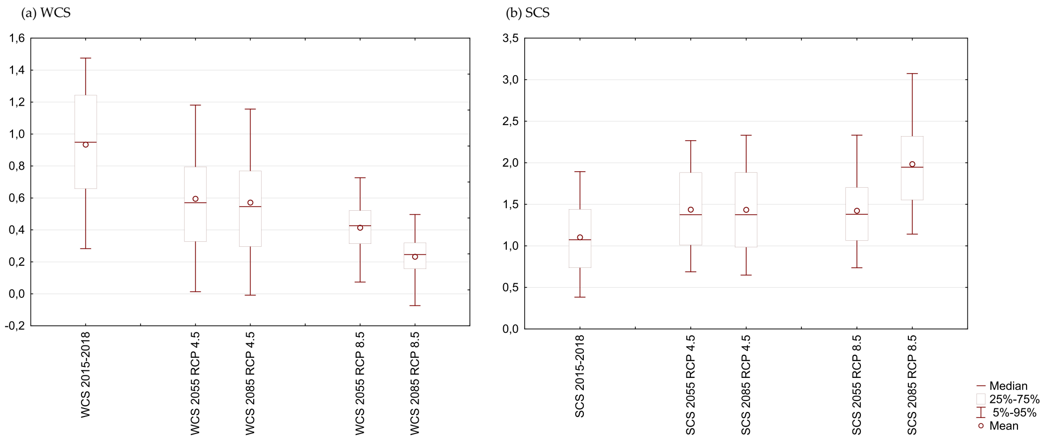


Figure 37. Box-plots of values of the WCS (a) and SCS (b) indeces in 7967 localities in peninsular Spain for the period 2015-2018 and future periods.

3.3.2. Proposed update of climate zones for peninsular Spain

Once the WCS and SCS of the 7967 localities for the period 2015–2018 and the RCP 4.5 and 8.5 scenarios have been obtained, based on Table 17, the new climate zones of the 7967 cities of peninsular Spain have been obtained. Figure 38 shows the geographical distribution of the CZs of CTE by 2015–2018 and the RCP 4.5 and 8.5 scenarios. To analyse the variation of the climate rating observed concerning the CTE, Table 18 shows the percentage of cities that vary this rating, while Table 19 shows the percentage of climate zones in the CTE in the period 2015–2018 and the RCP 4.5 and 8.5 scenarios.

Table 18. Dynamics of changes in climate zones according to scenarios.

scenario	winter CZ: code number of CZ that change	winter CZ: % of cities modifying CZ	winter CZ: % of cities that change CZ	summer CZ: code number of CZ that change	summer CZ: % of cities modifying CZ	summer CZ: % of cities that change CZ	winter+summer: % of cities that change CZ
2015–2018	1	47.2%	52.1%	1	58.7%	72.0%	84%
	2	4.4%		2	12.2%		
	3	0.1%		3	0.2%		
	4	0.1%		4	0.0%		
	5	0.1%		-1	0.9%		
	-1	0.1%					
RCP 4.5 2055	1	44.8%	89.0%	1	47.7%	88.6%	98%
	2	40.5%		2	39.4%		
	3	3.0%		3	1.4%		
	4	0.0%		4	0.0%		
	5	0.0%		-1	0.1%		
	-1	0.7%					
RCP 4.5 2085	1	41.0%	89.9%	1	48.3%	87.6%	98%
	2	43.4%		2	38.1%		
	3	4.7%		3	1.2%		
	4	0.1%		4	0.0%		
	5	0.0%		-1	0.1%		
	-1	0.7%					
RCP 8.5 2055	1	24.4%	92.4%	1	33.0%	82.7%	97%
	2	33.1%		2	25.5%		
	3	26.5%		3	18.9%		
	4	4.1%		4	0.0%		
	5	0.0%		-1	4.1%		
	-1	3.8%					
RCP 8.5 2085	1	10.1%	100%	1	31.0%	91.0%	98%
	2	36.7%		2	26.3%		
	3	35.4%		3	32.2%		
	4	11.6%		4	0.0%		
	5	0.0%		-1	1.1%		
	-1	0.6%					

Table 19. Percentage of climate zones in different scenarios

CZ	present		RCP 4.5		RCP 8.5	
	CTE	2015-2018	2055	2085	2055	2085
winter CZ						
α	0.00%	0.02%	0.15%	0.25%	0.41%	0.70%
A	0.74%	2.85%	12.89%	15.97%	16.62%	42.95%
B	5.47%	8.39%	29.21%	28.28%	53.39%	51.54%
C	20.05%	37.18%	43.54%	43.03%	28.28%	4.63%
D	44.90%	49.13%	11.60%	9.84%	1.27%	0.16%
E	28.76%	2.41%	2.59%	2.60%	0.01%	0.00%
summer CZ						
1	40.05%	8.65%	1.41%	2.11%	0.99%	0.38%
2	22.80%	23.79%	10.53%	11.83%	8.11%	0.44%
3	28.58%	38.21%	38.54%	36.45%	41.02%	13.83%
4	8.55%	29.35%	49.51%	49.60%	49.84%	85.31%
CZ (winter + summer)						
α3	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%
α4	0.00%	0.01%	0.15%	0.25%	0.41%	0.70%
A1	0.00%	0.00%	0.19%	0.23%	0.11%	0.18%
A2	0.00%	0.00%	0.04%	0.08%	0.01%	0.13%
A3	0.40%	0.13%	0.03%	0.14%	0.92%	2.82%
A4	0.34%	2.72%	12.64%	15.53%	15.54%	39.74%
B1	0.00%	0.19%	0.58%	1.04%	0.33%	0.04%
B2	0.00%	0.03%	3.00%	3.09%	5.35%	0.21%
B3	3.08%	0.65%	4.04%	4.31%	22.38%	9.62%
B4	2.40%	7.52%	21.57%	19.82%	25.26%	41.63%
C1	2.87%	5.57%	0.62%	0.77%	0.41%	0.11%
C2	3.21%	3.80%	4.10%	4.86%	2.45%	0.10%
C3	8.15%	13.93%	23.80%	23.89%	16.88%	1.37%
C4	5.81%	13.85%	14.90%	13.41%	8.50%	3.05%
D1	8.21%	2.42%	0.03%	0.08%	0.13%	0.05%
D2	19.58%	17.81%	3.26%	3.68%	0.30%	0.00%
D3	16.96%	23.49%	8.06%	5.51%	0.80%	0.03%
D4	0.00%	5.26%	0.25%	0.58%	0.04%	0.09%
E1	28.76%	0.39%	0.00%	0.00%	0.01%	0.00%
E2	0.00%	2.01%	0.05%	0.04%	0.00%	0.00%
E3	0.00%	0.01%	2.54%	2.55%	0.00%	0.00%

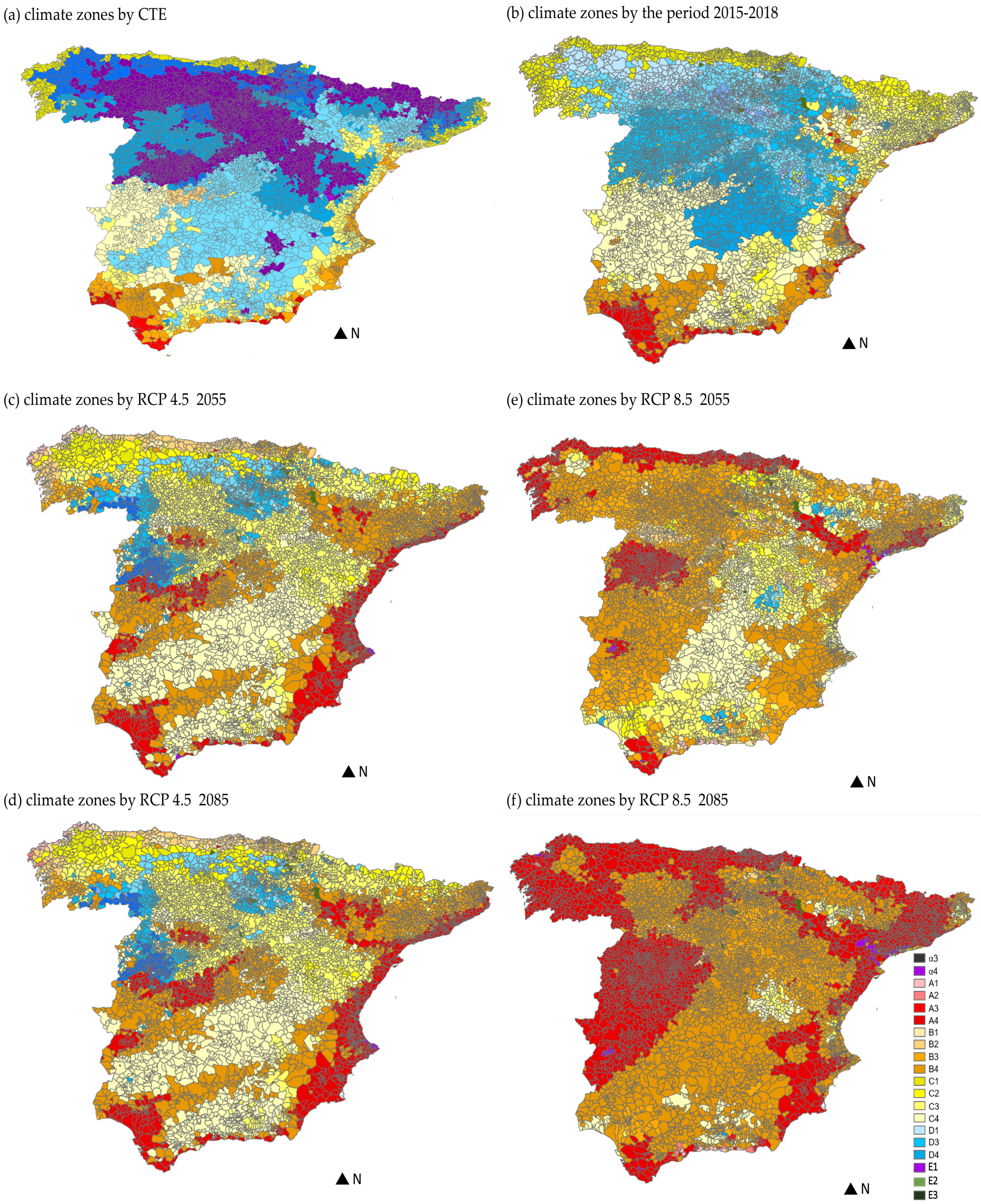


Figure 38. Maps of (a) climate zones CTE, (b) new climate zones, (c) climate zones for RCP 4.5 2055, (d) climate zones for RCP 4.5 2085, (e) climate zones for RCP 8.5 2055, (f) climate zones for RCP 8.5 2085 by 7967 localities in peninsular Spain.

3.3.2.1. Proposed update of climate zones for peninsular Spain for the period 2015–2018

Concerning the CTE in 2015-2018 (Table 18), more than 80% of the cities have already changed their CZ (winter + summer). Moreover, this change has meant that the number of climate zones in the country has increased from the 12 contemplated in the CTE to 19, with seven new zones appearing that were not previously re–categorised (α3, α4, B1, B2, D4, E1 and E2). The appearance of zones α3 and α4 should be highlighted, highlighting the trend, in areas such as the Mediterranean, towards climates more characteristic of subtropical zones.

In the case of winter, approximately half of the cities have changed their winter CZ to a warmer zone compared to the CTE (Table 18), although the most significant changes occur in the south and on the Mediterranean coast, while the CZs in the north, northwest, southwest and eastern part of Andalusia remain unchanged (Figure 38). The winter CZ D (Table 19) stands out, present in 49% of the localities, making it the predominant one. However, looking at the data for the 49 large cities, Figure 39 shows that a warmer zone will cover 17 cities compared to the CTE document, 7 of which will move from a D to a C rating.

This result shows a rise in winter temperatures in almost half of the territory concerning what is contemplated in the current regulations. The average increase in temperatures is causing a decrease in the energy demand for heating but implies that the limits of parameters such as transmittance are compromised. This can lead to inadequate management of resources, even generating pathologies such as humidity due to condensation, which can result in an unhealthy environment that ends up causing lung diseases, fungal growth and even uninhabitable housing.

In summer CZs, more drastic changes are observed, especially on the Mediterranean coast (Figure 38 and 39), due to the intense summer warming of the Mediterranean inland waters in recent years (Adloff et al., 2015). Thus for 2015–2018, 72% of cities have changed their summer CZs to warmer ones than those reported in the CTE (Table 18). Specifically, 58.7% and 12.2% of localities have changed their summer CZ to 1 and 2 warmer ratings, respectively. CZs 3 and 4 are the most predominant present in 38.21% and 29.35% of the localities.

In the same way, if the data of the 49 large cities are analyzed, the Figure 39, shows that in the case of the summer period, half of the cities will change their areas to warmer ones, compared to the CTE document zones. 25 cities show warmer climate zones in comparison with the CTE document; specifically, cities such as Girona and Ávila will change from zone 2 to zone 4 and from zone 1 to 3, respectively. Besides, CZ 4 is the most predominant, covering 45% of the cities, and the cities that have suffered the most significant variation are those located on the Mediterranean coast, due to the intense summer warming that the inland waters of the Mediterranean have experienced in recent years (Adloff et al., 2015).

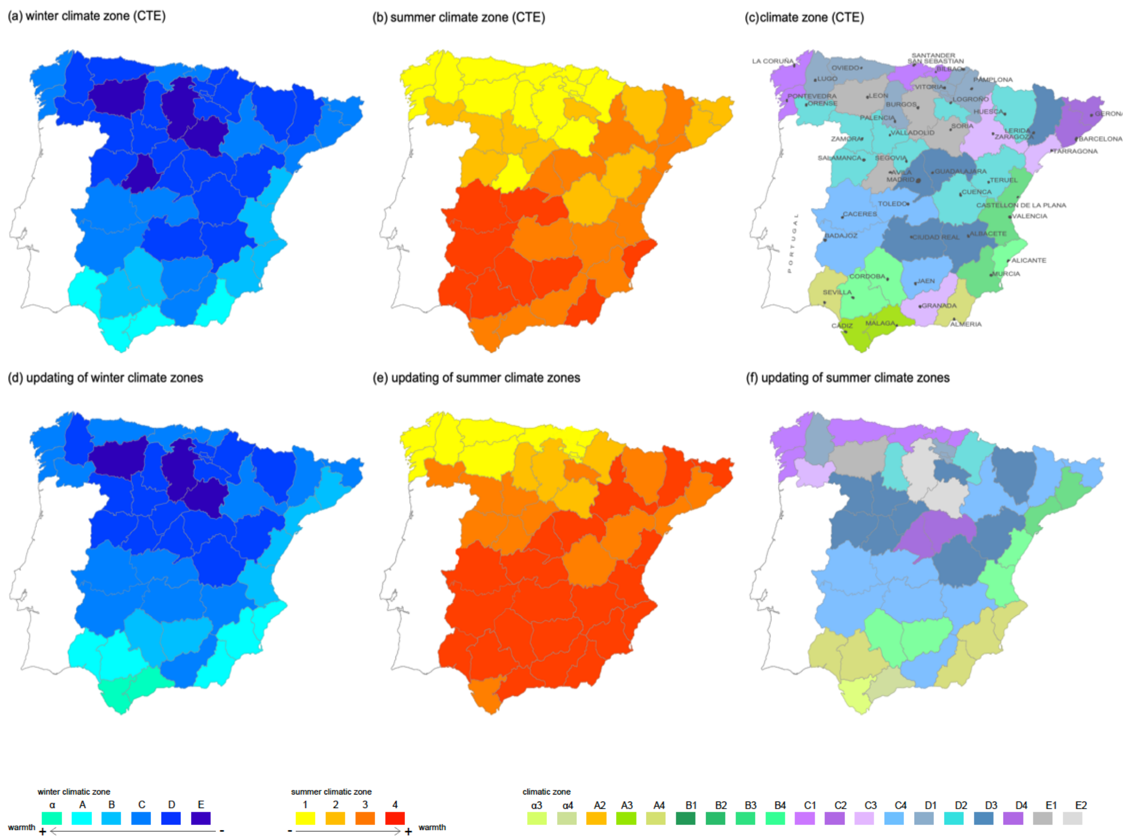


Figure 39. Maps of (a) winter CZ of CTE, (b) summer CZ of CTE, (c) CZ of CTE, (d) updating of winter CZ (2015–2018), (e) updating of summer CZ (2015–2018), (f) updating of CZ (2015–2018) by 49 cities in peninsular Spain.

3.3.2.2. Proposed climate zones for peninsular Spain for the RCP 4.5 scenario projections

Under the RCP 4.5 scenario (Table 18) for 2055 and 2085, 98% of the cities will see their CZ (winter + summer) change concerning the CTE. Furthermore, Figure 38 shows how the geographical distribution of climate zones for 2085 resembles the resulting distribution for 2055. These climate zone changes are a consequence of the closeness of absolute values of WCS and SCS to the limiting value of climate zone delimitation (Table 18) so that a minimal change of the index can lead to a change of CZ for a locality. This result is a limiting factor in the zoning of the existing CTE, reinterpreting the need for a significant improvement in the development and methodology of the current regulations in force.

As shown in Figure 38, by 2055 and 2085, half of the Mediterranean coastal localities will fall into CZ A4. These regions will be characterised by hotter summers and warmer winters, while the northern coastal cities will have a greater variety of CZs over the century, with mild summer temperatures and colder winters. The same occurs in the peninsula's interior, where a heterogeneous distribution is observed due to the complexity of the relief and the diversity of mesoclimatic and microclimatic zones. Thus, by 2085, 23.8% and 19.82% of the localities will have a C3 and B4 climate classification, while the coldest CZs will disappear (Table 19).

In winter CZs (Table 18), for the periods 2055 and 2085, practically 90% of the localities will change their climate zoning compared to that retained in the CTE. Specifically, for the period 2055, 44.8% of the localities will change their zoning to a warmer one and 40.5% of the localities to two warmer zones. Similarly, by 2085, 41%, 43.4% and 4.7% of localities will change their winter rating to 1, 2 and 3 warmer zones, respectively. Thus, the geographical distribution of winter CZs for 2085 resembles the resulting distribution for 2055, where only 8% of cities will observe zone changes between these two years. The increase of the A rating concerning the CTE (Figure 38 and Table 19), from 0.74% in the CTE to 12.89% and 15.97% in 2055 and 2085, respectively, stands out. In contrast, the E rating decreases drastically from 28.76% in the CTE to only 2.6% in 2085. These results again show that the trend towards warmer and warmer areas will continue throughout the century.

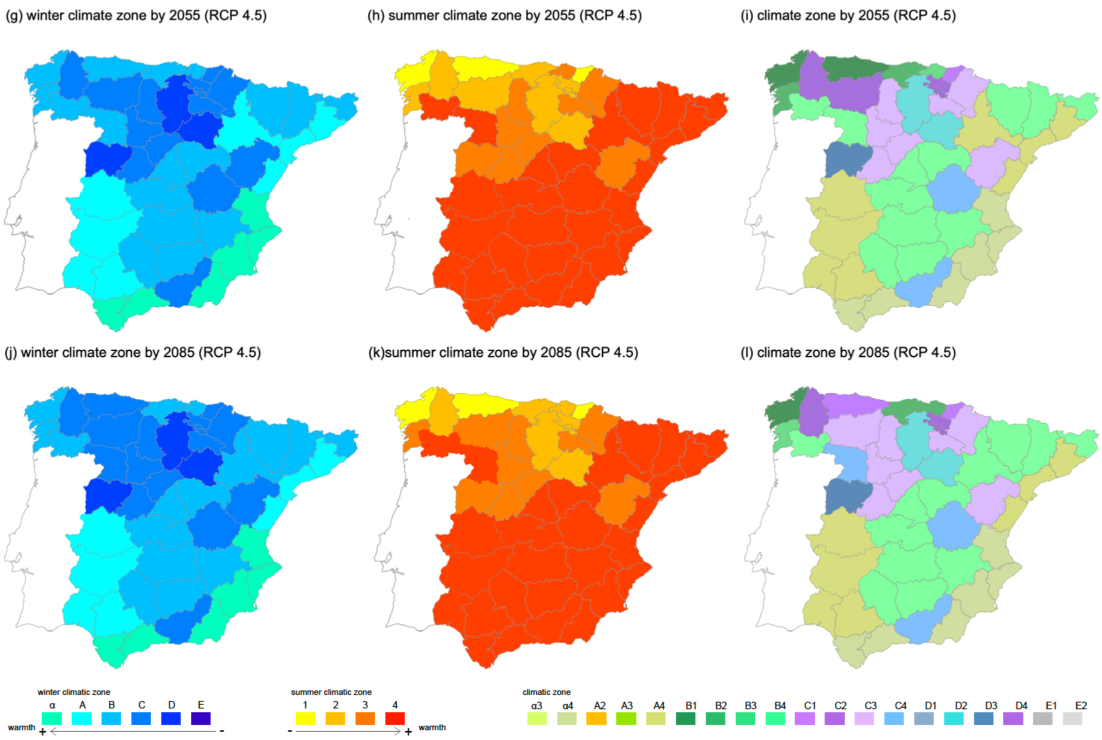


Figure 40. Maps of (g) winter CZ by RCP 4.5 2055, (h) summer CZ by RCP 4.5 2055, (i) CZ by RCP 4.5 2055, (j) winter CZ by RCP 4.5 2085, (k) summer CZ by RCP 4.5 2085, (l) CZ by RCP 4.5 2085 by 49 cities in peninsular Spain.

If we analyse the data for the winter areas of the 49 large cities, the Figure 40 shown that by the periods 2055 and 2085, Más del 90% of the cities will change their climate zones for warmer ones in comparison with the CTE document. Specifically, for the period 2055, 24 cities will change their classification to a warmer one and 21 cities will be two zones warmer (for example, Barcelona will change from zone C to zone A). Similarly, by 2085, 28 cities will have changed their zone to a warmer one, and 17 cities will be two zones warmer. This is because under the RCP 4.5 scenario, the period 2055 is slightly warmer than the period 2085, so only 8% of cities will observe zone changes between these two periods. Thus, in 2085 in cities such as Merida, Oviedo, Pontevedra, Santiago de Compostela, Zamora, and Zaragoza, there will be colder winter climate zones compared to 2055.

Besides, the geographical distribution of the winter climate zones for 2085 is similar to that for 2055. Finally, we see a significant increase in the presence of the qualification B concerning the CTE for 2055 and 2085; likewise, the qualification E disappears in both future periods.

In the summer CZs case (Table 18), for the periods 2055 and 2085, 88.6% and 87.6% of the locations will change their climate zonation compared to the CTE. By 2055, 47.7% of localities will change their zoning to a warmer one, and 39.4% of localities will change their zoning to two warmer zones. Similarly, by 2085, 48.3%, 43.4% and 38.1% of localities will change their summer rating to 1 and 2 warmer zones, respectively. As in the winter season, the differences between 2055 and 2085 are not significant. Although, throughout this scenario, there is a significant increase in rating 4 in the localities concerning the CTE (Figure 38 and Table 18), from 8.55% in the CTE to 49.51% and 49.60% in 2055 and 2085, respectively. In contrast, rating 1 decreases drastically from 40.05% in the CTE to only 2.11% in 2085. These results demonstrate the need to develop new summer zones within rating 4, with the consequent improvement in terms of building recommendations.

If we analyse the data for the summer areas of the 49 large cities, the Figure 40 shown that by the periods 2055 and 2085, more that the 70% of the cities will change their CZs for warmer ones compared to the CTE document. Of these, 10 and 11 cities changed to two zones warmer, in 2055 and 2085, respectively. As with the winter season, the differences between 2055 and 2085 are not significant, and only Bilbao will have a colder summer climate zone, and León a warmer one, for 2085 compared to 2055.

Furthermore, by 2055 and 2085, more of the middle of the cities will be located in climate zone 4. This is due to the increase in the average value of the SCS index=2.12 (st.dev.=0.37) for the hottest summer zone 4 in the year 2085, compared to SCS=1.87 (st.dev.=0.32) in the period 2015–2018.

3.3.2.3. Proposed climate zones for peninsular Spain for the RCP 8.5 scenario projections

Under the RCP 8.5 scenario (Table 18) for 2055 and 2085, a drastic increase in the change of CZ classification (winter + summer) concerning the CTE is foreseen, showing that 98% of the cities will be affected. Furthermore, Figure 38 shows that the geographical distribution of CZs for 2085 will undergo a significant dynamism, with zones A4 and B4, with 39.74% and 41.63%, dominating the peninsula. These zones are characterised by mild winters and sweltering summers, leading the peninsula to have climates more typical of tropical regions by the end of the century.

In the winter CZs (Table 18), for the periods 2055 and 2085, 92.4% and 100% of the locations will change their climate zoning compared to the CTE. Specifically for the period 2055, 24.4, 33.1, and 26.5% of the localities will change their qualification by one, two and three warmer zones, respectively. Similarly, by 2085, 10.1, 36.7, and 35.4% of localities will change their winter rating to one, two and three warmer zones, respectively. Throughout this scenario, there is a significant increase in the presence of the A and B rating in the localities concerning the CTE (Table 17), from 0.74 and 5.47% in the CTE to 42.95 and 51.54% in 2085, respectively, on the contrary, the C and D ratings decrease drastically, while the E climate zone disappears entirely by

2085. These results are due to the already indicated trend towards warmer and warmer zones.

However, if we analyse the data for the winter areas of the 49 large cities, the Figure 41 shown that by winter climate zones by 2055, 90% of the cities will change; specifically, 27 cities will change their rating to one warmer and 17 to two warmers (for example, Barcelona will change from zone C to zone A). However, between the periods 2055 and 2085, 57% of cities will change their classification, compared to 8% in the RCP 4.5. This is due to the specifications of this scenario mentioned in the previous section. By the period 2085, all cities will change their winter CZ to warmer ones concerning the CTE. Specifically, three cities will change their rating to be three levels warmer (from D to A and from C to α), and 32 to two levels warmer. It should be noted that, as in the case of the RCP 4.5 scenario, the E rating will disappear for both future periods and the D rating for 2085 in the RCP 8.5.

In the summer CZs case (Table 18), for the periods 2055 and 2085, 82.7% and 97% of the localities will change their climate zoning compared to the CTE. By 2055, 33% of the localities will change their zoning to a warmer one, 25.5% of the localities to two warmer zones, and 18.9% to three warmer zones. Similarly, by 2085, 31%, 26.3% and 32.2% of localities will change their summer rating to 1, 2 and 3 warmer zones, respectively. In Figure 38 significant differences are observed between 2055 and 2085. Throughout this scenario, there is a significant increase in the presence of rating 4 in the localities concerning the CTE (Table 18), from 8.55% in the CTE to 49.84% and 85.31% in 2055 and 2085, respectively, in contrast, rating

1 decreases drastically from 40.05% in the CTE to only 0.38% in 2085. These results show that more than half of the buildings designed with zone E's technical requirements will not comply with the regulations in less than 25 years. However, if we analyse the data for the winter areas of the 49 large cities, the Figure 41 shown that by the periods 2055 and 2085, 69% and 82% of the cities will change their CZs for warmer ones compared to the CTE . Thus, 12 and 17 cities change their zones to be two levels warmer, in 2055 and 2085, respectively. It should be noted that in 2085, 4 cities will change from having a rating of 1 (the coolest for summer) to a rating of 4. As with the winter season, the differences between 2055 and 2085 are significant, with 39% of cities changing their summer rating.

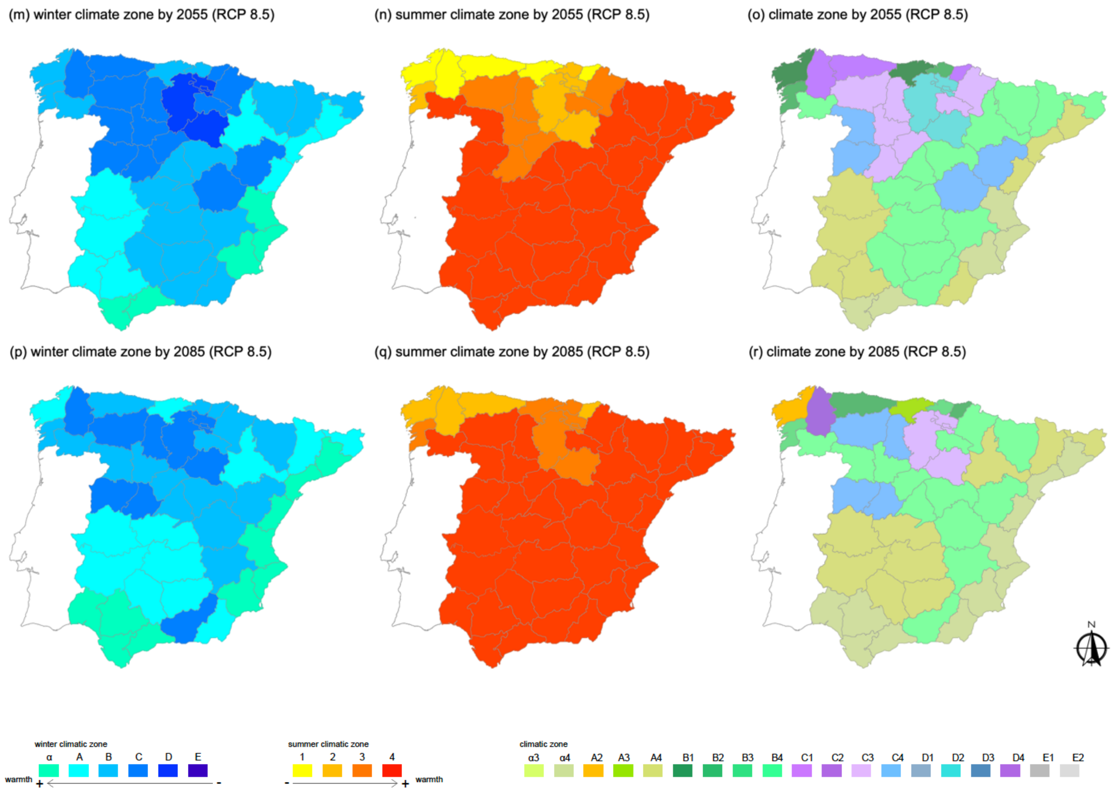


Figure 41. Maps of (m) winter CZ by RCP 8.5 2055, (n) summer CZ by RCP 8.5 2055, (o) CZ by RCP 8.5 2055, (p) winter CZ by RCP 8.5 2085, (q) summer CZ by RCP 8.5 2085, (r) CZ by RCP 8.5 2085 by 49 cities in peninsular Spain.

3.4. Analysis of the dynamics of changes in energy demand for RCP 4.5 and RCP 8.5 scenarios

In order to analyse the effects that the observed climate dynamism will have on the energy demand of buildings, Figure 42 shows the average results of the estimated change in for heating and cooling energy demand, calculated based on the definition of the WCS and SCS indices of the 77 stations, for the typical building used for 2015-208 and the RCP 4.8 and RCP 8.5 scenarios. Besides, Table 4 shows the estimated for heating and cooling energy demand, for four significant stations, for the building type used for 2015–208 and the RCP 4.8 and RCP 8.5 scenarios.

In the RCP 4.5 scenario (Figure 42), by the year 2055, the energy demand total of the 77 stations is expected to decrease by an average of 11.23 kWh/m^{2}year compared to 2015-2018. Specifically, heating energy demand will decrease by an average of 16 kWh/m^{2}year, with the most significant decreases observed in stations located in mountainous areas at 900 metres above sea level; this is due to the notable effect of the continental climate, which will see its meteorological conditions soften in winter due to the effects of climate change. Such is the case of station 73, located in Valladolid, with a reduction of 32 kWh/m^{2}year. However, cooling energy demand will increase by an average of 4.8 kWh/m^{2}year, compared to 2015–2018, in cities located in the southeast, characterised by a semi–arid climate; specifically, station 5, located in the city of Almeria with an increase in cooling energy demand by 2055 of 7.045 kWh/m^{2}year compared to 2015-2018. However, due to this climate scenario's stabilising nature between 2055 and 2085, no significant differences are observed between the average demand values for heating and cooling energy demand, with an average increase of only 0.8 kWh/m^{2}year.

Under the RCP 8.5 scenario (Figure 42), by the year 2055, heating and cooling energy demand for all seasons are expected to decrease by an average of 10 kWh/m^{2}year compared to 2015–2018. Specifically, heating energy demand will decrease by an average of 15.4 kWh/m^{2}year, highlighting station 17, located in the city of Castellón, where a high reduction value, estimated at 30 kWh/m^{2}year, is foreseen. In contrast, cooling energy demand will increase by an average of 5.3 kWh/m^{2}year compared to 2015–2018. Station 5, located in Zaragoza, stands out in particular, with an increase in cooling energy demand by 2055 of 16.7 kWh/m^{2}year compared to 2015-2018. It should be noted that, unlike the RCP 4.5 scenario, under the scenario, there are significant differences between 2055 and 2085. Thus, by 2085, the average heating energy demand will decrease by 8.2 kWh/m^{2}year, while the cooling energy demand will increase by 8.7 kWh/m^{2}year compared to 2055. This trend is localised in cities located in the south-western, southern and Mediterranean coastal parts of the country. These results are explained by expanding the semi–arid climate that the south and southeast coast will undergo under this scenario, where summers will be hotter and drier, significantly increasing the cooling energy demand of dwellings. This increase will also be affected by the additional thermal effect of the Mediterranean Sea's warming surface waters.

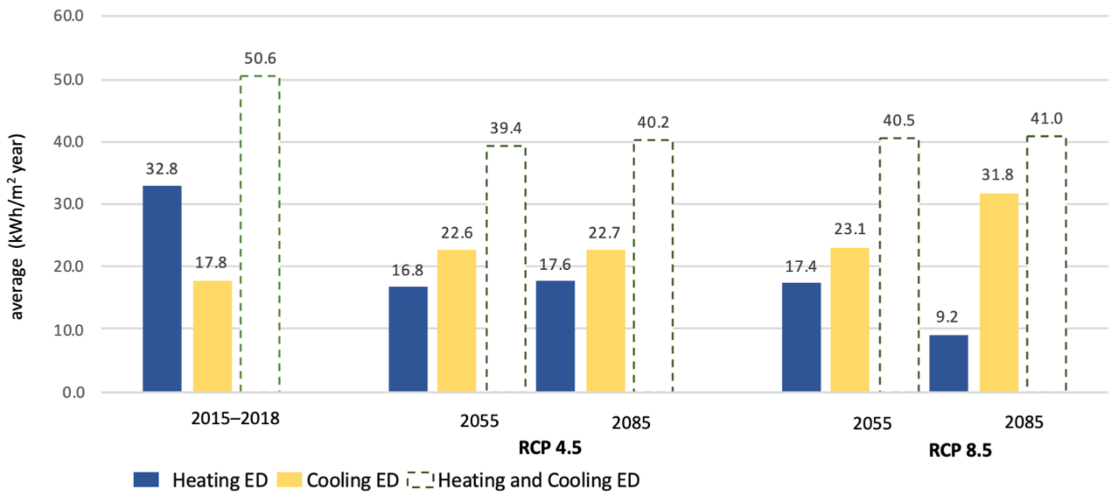


Figure 42. Dynamics of changes in the average of heating and cooling energy demand for the RCP4.5 and RCP8.5 scenarios by 77 station.

Table 20. Dynamics of changes in energy demand between significant seasons

WS	2015–2018 ED[d]			RCP 4.5 2055 ED			change ED between 2015–2018 and 2055		RCP 4.5 2085 ED			change ED between 2015–2018 and 2085	
	H[a]	C[b]	H + C	H	C	H + C	H	C	H	C	H + C	H	C
73	64.5	10.7	75.2	32.5	13.5	46.0	32.1	-2.8	33.8	13.5	47.3	30.8	-2.8
5	8.5	24.7	33.2	5.1	31.7	36.8	3.4	-7.0	4.7	35.5	40.2	3.8	-10.8
17	28.6	17.5	46.1	11.1	23.1	34.2	17.5	-5.6	11.5	22.8	34.4	17.1	-5.4
76	14.5	22.3	36.8	10.7	29.0	39.7	3.8	-6.8	9.4	27.9	37.3	5.1	-5.6

WS[c]	RCP 8.5 2055 ED			change ED between 2015–2018 and 2055		RCP 8.5 2085 ED			change ED between 2015–2018 and 2085	
	H	C	H + C	H	C	H	C	H + C	H	C
73	33.8	13.8	47.6	30.8	-3.1	23.5	21.4	44.9	41.0	-10.7
5	12.8	8.9	21.7	-4.3	15.8	6.4	14.1	20.5	2.1	10.6
17	-2.1	32.3	30.1	30.8	-14.8	-7.3	41.6	34.3	35.9	-24.1
76	-0.9	39.0	38.2	15.4	-16.8	-6.4	48.5	42.1	20.9	-26.2

[a] Heating, [b] Cooling, [c] Weather station, [d] Energy Demand

4. Discussion

The results show that most of the territory of peninsular Spain will be evolving into warmer CZs in a short period. In particular, Spain will soon see milder winters and warmer summers. Thus, in the future, Spain will have climates similar to those of the current countries of North Africa such as Morocco, Tunisia or Algeria. Specifically, most regions of Spain will be located in areas with negative WCS indices, which imply a decrease in the demand for heating in homes, but a very significant increase in the demand for cooling. Of course, the results of this study, based on a slightly simplified methodology, can be improved and refined by using hourly temperature data from an ensemble of regional climate models for future periods, as well as data on changes in hours of sunshine duration. It should be noted that the problems in Spain can be extrapolated to most countries in Mediterranean and Subtropical regions, where the current lack of rules or regulations on the adaptation of buildings to climate change results in obsolete building stock, which is unable to cope with the climatic dynamism that is already occurring.

Consequently, it is essential to adopt new climate zones that take climate dynamism into account. Thus, one solution to this problem could be to create new summer climate zones and technical requirements for building. Another solution would be to adopt the climate zones of those countries already experiencing the climate conditions that Spain can expect to have in future.

On the other hand, it should be noted that the literature analysis for this study did not find any examples of the development or implementation of dynamic building standards and requirements that take into account the changing climate zones. However, it should be noted that the key to the successful development of such building standards is a precise and reproducible methodology. For example, in Canada's case (NRC IRC, 2011), a methodology similar to ASHRAE climate zoning is used (ASHRAE, 2013). This methodology makes it possible for the whole country to determine the evolution of climate zones in the future and to adjust building standards and requirements for different geographical locations, because, most likely, the warmer climate zones, which currently only exist in the United States, will in the future move to the territory of Canada. On the other hand, for the United States, the existence of climate zones 0A and 0B in the ASHRAE building code (ASHRAE, 2013) may provide a particular buffer of time for the development of dynamic building standards until these zones appear in the United States and then move northwards.

5. Conclusions

In this chapter, the basis is laid for the approach of strategies aimed at establishing local regulations and standards to demand sustainability criteria and adaptation to climate change in the building by identifying climate dynamism and its impact on the building. This work is fundamental for the correct evaluation of sustainability throughout the building's life cycle, being key for the development of SBAMs.

Therefore, the CZs of all the cities of peninsular Spain have been updated. The results show that the allocation of CZs currently included in the CTE is not suitable for current and future climatic conditions. Given the importance of precision in the assignment of a CZ when correctly sizing domestic hot water, heating and cooling systems and the appropriate selection of the construction materials used, this situation jeopardises the achievement of truly sustainable buildings. Specifically, taking into account the climate data recorded in the 2015-2018 period, 80% of cities today have a different climate zone to that of the CTE; moreover, it is expected that by the year 2085 and under the forecasts recorded in the RCP 4.5 and RCP 8.5 scenarios, practically all cities in mainland Spain will change their climate zone to warmer ones.

This significant climate change that the region under study is already undergoing will help reduce the heating energy demand of dwellings and increase the demand for cooling. Therefore, architectural and construction standards must adapt to the urban environment's actual conditions and consider the main scenarios to lead to a building design that mitigates climate change and adapts to them. It intensifies the need to develop new climate zones and build recommendations to preserve future periods' correct thermal conditions.

Finally, it should be noted that the consequences observed in peninsular Spain can be extrapolated to other areas so that the methodology proposed in this work can be extrapolated to any region, making a significant scientific contribution in terms of reflection on the current capacities and possibilities for improvement of the building stock.

CHAPTER 5 Identifying public policies to promote sustainable building: a proposal for governmental drivers based on stakeholder perceptions[5]

[5] The results shown in this chapter are under review in: C. Díaz-López, A. Navarro-Galera, M. Zamorano, D. Buendía-Carrillo. Identifying public policies to promote sustainable building: a proposal for governmental drivers based on stakeholder perceptions. Sustainability

1. Introduction

The other strategy proposed in the analysis of Level(s), in chapter 3, by the experts to promote sustainability criteria in building at different stages of the building's life cycle has been the use of fiscal incentives (taxes or fees) or economic incentives (funding or aid). Their development would remedy the barriers identified and related to the lack of instruments and mechanisms to encourage the implementation of sustainability criteria and, therefore, their evaluation.

At present, many countries are currently facing the challenge of adopting and implementing integrated measures, policies and plans aimed at inclusion, resource efficiency, mitigation and adaptation to climate change in their building stock. However, despite these exciting initiatives, one of the main problems for developing this new paradigm of sustainable building stock is the remaining concern about financing for housing acquisition, taxation and long–term amortisation.

On the one hand, the high initial capital costs and low market value, compared to conventional construction, create a dilemma for stakeholders (Salem et al., 2018). On the other hand, there is a lack of urgency in implementation, as current generations of policymakers will be gone by the time the most severe effects of climate change are felt. Besides this, the dispersion of competences between different government levels (central government, regional governments and local governments) and many stakeholders in the process slows down the proper development of sustainable building.

In this sense, public authorities' involvement (responsible for policy formulation and the implementation of enforcement measures) is seen as an effective mechanism to promote sustainability criteria in construction (Dell'Anna & Bottero, 2021; Carmen Díaz-López et al., 2021). However, it is not only governmental bodies that are stakeholders in sustainable building. In the context of sustainable construction, stakeholders are individuals or groups that have a specific interest in sustainable housing projects because their decisions affect the development of these projects and may be affected by the outcome. Stakeholders include: developers, construction companies, governments, homebuyers, banks, and public employees with responsibilities for urban planning (Parmar et al., 2010).

On this basis, previous research findings and international pronouncements (such as the SDGs) acknowledge the environmental, social and economic benefits of sustainable buildings and recognise the need for government incentives to encourage the adoption of sustainability criteria in the building sector (Adabre et al., 2020; Carmen Díaz-López et al., 2021; Q. Li et al., 2020; Martek et al., 2019; Martiskainen & Kivimaa, 2019; X. Yang et al., 2019). In general, incentives can be defined as something that influences people to act in specific ways (Kemmerer & Thiagarajan, 1989). Stakeholders can influence and share control over development initiatives and measures, as well as the decisions that most affect them. Therefore, it is of great interest to consider the expectations and needs of all stakeholders in analysing the measures that governments can put in place as effective instruments for reducing the environmental impact of the building sector.

On this basis, taking into account the wide variety of instruments (from national to local and from fiscal to financial) available to governments around the world, it is necessary and timely to identify concrete drivers (or stimulating factors) that enhance the implementation of sustainability criteria from a stakeholder’s perspective, including all three aspects of sustainability (environmental, economic and social) throughout the whole life cycle of the building.

From this motivation, this paper's main objective is to find drivers that governments could adopt to enhance sustainability in housing construction, renovation and use, based on stakeholder perceptions. To meet this objective, we have conducted an opinion survey among a wide range of sustainable building stakeholders. Our findings are exciting and novel for the design of public policies to enhance sustainability in housing construction and use; they may help countries that are interested in implementing governmental measures on sustainable building.

Although research on drivers in the construction industry is vast, no studies have been published that have covered the diversity of drivers of various categories related to the whole building life cycle and from all stakeholders' perspectives. With its holistic and comprehensive approach, this work is an important step forward, as it provides new knowledge that is highly relevant for the development of a sustainable, inclusive and resilient building stock from the perspective of all stakeholders.

2. Previous research and background

2.1. Previous research

There are different approaches in the academic literature relating to drivers (incentive measures) for sustainable buildings, depending on the type of instrument. On the one hand, we observe those works related to the option of implementing fiscal incentives, forcing compliance with specific conditions or requirements implemented by governments (Aliagha et al., 2013; Perkins & Mcdonagh, 2012). Works such as Kong and He (Kong & He, 2021) analysed China's incentive policies for sustainable buildings, highlighting their non-existence until 2013.

On the other hand, authors such as Love et al. (Love et al., 2012) defended the benefits of sustainable buildings for adopting sustainable construction practices. Thus, as Andelin et al. (Andelin et al., 2015) point out, progress concerning sustainability in construction depends on people in the sector being aware of the importance and possibilities offered by sustainable buildings and the ability and willingness to act on this knowledge. Other authors, such as Rana et al. (Rana et al., 2021), reviewed incentives such as taxes, loans, grants and rebates available for sustainable buildings in Canada, although they only focused on energy performance. Falkenbach et al. (Falkenbach et al., 2010) analysed sustainability drivers for real estate investors. Qi et al. (Qi et al., 2010) identify those incentives that influence contractors to adopt sustainable construction practices through a survey. Other works include critiques and strategies to improve government incentives. Zuo and Zhao (Zuo & Zhao, 2014) identied those incentives that influence contractors to adopt sustainable construction practices, through a survey.

Other works include criticisms and strategies to improve government incentives. Zuo and Zhao (Zuo & Zhao, 2014) pointed out that there has not been a comprehensive description of incentives as a tool to drive the adoption of sustainable building. Despite their differences, most researchers agree that tax-based and voluntary drivers can stimulate the adoption of sustainable buildings. However, no work has so far been published that fully and comprehensively analyses a wide variety of drivers through the perception of different stakeholders, which justifies the interest and opportunity of our research to advance knowledge on how to enhance the sustainability of dwellings, including construction, refurbishment and use in their life cycle.

2.2. The role of drivers around the world

Many countries around the world are implementing drivers to promote sustainable building. These drivers are usually fiscal (obliging the user to adopt specific sustainability criteria) or voluntary in nature, providing incentives through subsidies or other types of sustainability mechanisms in buildings (Camarasa et al., 2020b).

In Europe, governments in countries such as Spain have established subsidies and loans to construct new buildings and their refurbishment with energy efficiency measures. In the Czech Republic, there is a building renovation scheme (The New Green Savings scheme, 2019) that has provided more than 2 billion CZK in subsidies to 9088 projects, focusing on energy renovations (New Green Savings Programme, 2019). In Finland, the Energy Certificate Act requires owners to obtain an energy certificate and building permit procedures for new buildings when selling or renting (Åkerman et al., 2020). Besides this, the Building and Land Use Act ensure that land and water areas and construction activities create preconditions for favourable living environments and promote ecologically, economically, socially and culturally sustainable development.

In the UK, the enhanced capital allowance scheme allows a 100% deduction of the investment cost in qualifying energy–saving technology, although there are no specific incentives for the building itself (Malinauskaite et al., 2019). In France, there are some specific incentives for green building. Thus, buildings that have received a Low Energy Consumption in Buildings label are partially or fully exempted from property tax. Such exemption applies up to 100%, depending on the local authorities' decision, which also determines the exemption period. In the Netherlands, depreciation allowances are granted for environmentally friendly assets in Arbitrary depreciation environmental investments (VAMIL). It is possible to deduct up to 36% of capital outlay from the taxable profit, in addition to regular depreciation (Majcen et al., 2016).

In Poland, the National Fund for Environmental Protection and Water Management offers incentive programmes for constructing energy–efficient houses or the purchase of energy-efficient flats (Woźniak et al., 2020). Subsidies are granted in the form of partial reimbursement of the bank loan for the construction/purchase of a house. Incentives are also available to construct new energy–efficient public buildings, collective residences, thermal efficiency improvements, and energy-saving investments. In Portugal, property transfer tax can be exempted if a buildings' energy efficiency is upgraded, in specific urban properties. Localities may also apply a reduction to the municipal property tax rate applicable to urban properties considered ‘green’ or ‘energy–efficient’, based on energy consumption (OECD, 2019). Switzerland's ‘Building Programme’ incentivises house renovation to increase the insulation of windows, walls, roofs and floors.

On the other hand, regional programmes have been implemented in Canada, such as in Hamilton, where there is a tax exemption of up to 75 % of the property tax expected to accrue on a new, sustainable building. Colombia has established minimum water and energy savings per year that new buildings must achieve, depending on their location. Localities and districts are also encouraged to establish incentives to increase these minimum water and energy savings rates. There is also a project to establish guidelines for the National Sustainable Construction Policy, to provide economic benefits and financial (and other) incentives that can be created to promote sustainable construction in Colombia (Zabaloy et al., 2019).

In Mexico, there are no federal fiscal incentives for green building, although local incentives do exist. For example, Mexico City offers property tax reductions for certified sustainable buildings (Saldaña-Márquez et al., 2018). Similarly, in New Zealand, there are no major government incentives for the construction or occupation of green buildings. Local governments must adopt a 'sustainable approach to urban planning and building' however, there is no further guidance or structure. The New Zealand Building Council provides resources and rating systems rather than incentives.

In Singapore, the government launched the Green Mark Scheme in 2005, to promote sustainability in the built environment and raise environmental awareness among developers, designers, and builders from project conceptualisation and design through to construction. To encourage the private sector to construct buildings that achieve the highest Green Mark ratings, they have introduced a set of incentives, benefiting up to 50% of eligible costs incurred exclusively to improve energy efficiency in buildings (Chiu et al., 2017).

Thailand does not provide incentives for green buildings. However, the Energy Conservation Promotion Act establishes obligations and responsibilities (e.g. construction or retrofit criteria) for certain types of buildings with a total floor area of 2000 m^2 or more, such as hospitals, schools, offices, convention centres, theatres, hotels, entertainment venues and department stores. Besides this, certain types of buildings have additional obligations, for which non-compliance may result in special electricity charges and criminal fines (Damrongsak & Wongsapai, 2017).

As can be seen, despite the interest in these initiatives and the relevant findings of previous research, most studies and policies have focused on one aspect of sustainability (namely energy efficiency) without considering the complete life cycle of the building. Therefore, other elements of sustainability in buildings have not yet been sufficiently analysed to date. These include: the performance, cycle, use and monitoring of different water sources; the use, recycling, reuse and environmental impact of materials and resources; the reduction, control, consumption and use of energy, environmental ergonomics, designs, processes and strategies that promote sustainability in the built environment; the use of traditional local materials and techniques; the use of resources and reuse of building materials, systems and subsystems; and the ability of buildings to adapt to climate change (and its consequences) without damage.

Therefore, more research is needed to identify governmental drivers, considering the different government levels that can make decisions and the wide variety of instruments available to analyse the whole building life cycle, which motivates the timeliness and interest of the present paper. Our empirical results show an advance on previous research findings and are helpful for different countries.

3. Materials and methods

In order to identify governmental drivers for sustainable building, we used the following methodological phases: (i) sample selection; (ii) selection of potential drivers; (iii) design and execution of the opinion survey; and (iv) analysis of the results.

Given the global nature of the subject studied in this chapter Spain was selected as a very appropriate territory for the empirical study to be carried out. The construction sector generates a high percentage of the gross domestic product (GDP) in Spain, 5% in 2019. Besides this, the importance of taxes derived from the construction sector and its preference for purchasing real estate capital over renting (77% of citizens are owners) is almost 10 points more than the European average. The low percentage of investment in sustainable building and the fact that the tax burden on home ownership has resulted in Spain being one of the EU countries with the highest proportional taxes on property ownership.

Moreover, since the public management model for building in Spain is similar to that of other countries, our methodology and results should be an interesting reference for governments in other countries interested in promoting sustainable building. Finally, the study focused on residential buildings, given that residential buildings have the most significant environmental, economic and social impact on the rest of the building typologies.

3.1. Selection of the sample

The first phase of the methodology was to select stakeholders, based on the so–called Stakeholders Theory. According to Freeman and Mcvea (R. E. Freeman & McVea, 2005), a stakeholder is a group or individual that can affect or be affected by an organisation's efforts to achieve its objectives. This theory holds that management's goal (including government) is the long-term maximisation of stakeholders' welfare (R. Freeman et al., 2007). Friedman and Miles (Friedman & Miles, 2006) stated that Government policies should be guided by the needs of the people who can influence their decisions. According to these postulations, the academic literature highlights the importance of stakeholder participation in implementing sustainability criteria in buildings at all stages of the life cycle (AlWaer & Kirk, 2012; Camarasa et al., 2020a; Fu et al., 2020; Z. P. Lee et al., 2020; López et al., 2019). Thus, for the selection of those surveyed, the following questions were established:

- Who are the stakeholders that can influence (or be affected by) the environmental and socio-economic impact of building, retrofitting and use of residential housing?
- Who can improve the sustainability of residential housing construction and retrofitting by the life cycle stage?

Thus, based on these issues, 19 types of stakeholders were identified, see Table 21. The 19 stakeholders represent the private and public sector and cover all actors involved in the building's life cycle.

Table 21. Detailed composition of the panel of stakeholders.

stakeholders		first round answers	second round answers
Building professionals (architects and engineers)	Technical building professionals	6	72
	Local administration technician	1	14
	Technician of the autonomous administration	5	9
	Technician from the state administration	1	5
	Technician with political links	1	3
Policy	Politician or policy at local level	1	4
	Regional level politician or policy	1	1
	Politician or politician at state level	1	1
Organisations	Professional associations	2	47
	Universities and research centres	4	11
Owners and users	Homeowner with only one dwelling and in use	4	17
	Owner with two dwellings, both in use	2	9
	Owner with one empty dwelling	2	4
	Owner of a dwelling that is rented out	1	1
	Landlord/landlady	1	1
Financial institutions	Financial institutions	2	8
Builders and developers	Builder	2	9
	Developer	2	8
	Builder and developer	1	5
	Total	40	229

3.2. Identification of potential drivers

In the second stage, potential drivers for the promotion of sustainability criteria in housing were identified. Following previous research (Aliagha et al., 2013; Perkins & Mcdonagh, 2012), the drivers can be fiscal, financial and governmental interventions. Fiscal drivers take the form of rebates on the payment of certain tax obligations granted to taxpayers to promote the performance of specific activities considered of interest by the public sector. Financial drivers enhance the interest of sectors to reduce cost and increase market demand, e.g. setting a feasible price for energy, tax deduction programmes, efficient products, subsidy programmes, and financial support. The drivers of government interventions represent governmental bodies' role through education, training, information publication, and technical support (Shazmin et al., 2016). In any case, we paid particular attention to the set of drivers to be assessed in the survey that meet the following requirements:

- be clear, concise and legally supported according to the territorial context of the application,
- cover the entire life cycle of the building, from the conceptual design stage to the demolition stage,
- cover all aspects of sustainability (environmental, economic and social) and represent all possible casuistry, from fiscal to financial, without forgetting other drivers for the promotion of sustainability.

Based on the established criteria and following the regulations in force in the different areas, Table 22 identifies 41 drivers that could be adopted by the different governmental bodies in Spain to enhance the sustainability of the building, renovation, and residential housing. These drivers are classified into three categories, 30 fiscal drivers, divided into taxes and charges; five financial drivers; and six drivers related to government interventions. These drivers are based on the regulations that are in force and directly related to the building process in Spain.

Table 22. Drivers identified (part 1).

Driver		Definition
Fiscal. Deductions and allowances in Taxes		
1	Personal Income Tax (IRPF)	Personal Income Tax or IRPF is a personal, progressive and direct tax on the income obtained in a calendar year by individuals resident in Spain.
2	Corporate Income Tax (IS)	IS is a tax levied on the income of companies and other legal entities. Corporate income tax is a tax levied on the profits made by companies and other legal entities.
3	Urban Property Tax (IBI)	IBI is a compulsory, direct, actual, objective, and periodic local tax levied on real estate's value regardless of its product or the income derived from it.
4	Tax on Increase in Value of Urban Land (IIVTNU)	The IIVTNU, also known as municipal capital gains tax, is a tax within the local tax system in Spain levied on the increase in value of urban land at the time of transfer.
5	Tax on unoccupied dwellings.	Whether it is in the city, on the beach or in the mountains, the owner of an unoccupied property has to charge real estate income to personal income tax. The amount to be paid is calculated based on the property's cadastral value and depending on whether or not this cadastral value has been revised.
6	Tax on Economic Activities (IAE)	The IAE is a tax that forms part of the Spanish tax system managed by the local councils. It directly taxes the performance of any economic activity, both individuals and legal entities. Unlike other taxes, its amount is constant regardless of the balance of the activity. It is a direct, compulsory, proportional, accurate and shared management tax.
7	Value-Added Tax (VAT)	Value-added tax (VAT) is an indirect consumption tax and is levied, in the manner and under the conditions laid down by law, on the following transactions: the supply of goods and services carried out by entrepreneurs or professionals.
8	Tax on the manufacture of electricity	The electricity tax is fixed by law. This means that no one is exempt from paying it and that, even if no electricity consumption is made during a month, it will be applied to the contracted power. Therefore, the electricity tax can be controlled through consumption and contracted power since it is a figure obtained from a percentage of both terms. Besides, the 21% VAT is also levied on this electricity tax, so that in the end, you are paying a much higher amount of tax than was initially apparent.
9	Tax on constructions, installations and works (ICIO)	The ICIO is an optional tax, the taxable event of which is the carrying out, within the municipality, of any construction, installation or work, for which a building or urban planning licence is required, and the issuing corresponds to the town council.
10	Transfer Tax and Stamp Duty (ITP)	ITP is an indirect tax levied on three taxable events. This tax is levied on the purchase of second-hand property and rentals and legal acts, such as the public deed of sale of a property or the deed of a mortgage execution.

Table 22. Drivers identified (part 2).

Driver	
Fiscal. Reduction of taxes	
A fee or charge is a consideration for the provision of public service by local government bodies. A fee is a charge paid by the individual taxpayer for the provision and maintenance of public service.	
11	Water supply service charges
12	Sewerage service charges.
13	Refuse collection service charges
14	Waste treatment service taxes
15	Sewerage levy rates
16	Taxes for the provision of basic services
17	Taxes for planning permission
18	Taxes for certificates of occupancy and first occupation licences
19	Vehicle parking taxes
20	Vehicle entry taxes
21	Taxes for the opening of trenches and ditches.
22	Taxes for occupation of public roads with temporary suspension of road traffic
23	Taxes for the use of the flight
24	Taxes for the execution of works
25	Taxes for urban development actions
26	Development taxes
27	Urbanisation taxes
28	Urban development taxes
29	Taxes on real estate rentals
30	Taxes on rentals of urban property
Financial. Granting of financial benefits.	
31	Climate bonds or green bonds
32	Non-repayable grants (subsidies)
33	Preferential low-interest financing
34	Long-term preferential financing
35	Financing of public services
Government interventions	
36	Increasing the level of buildability
37	The possibility of change of use of the building and/or part of it
38	The provision of sustainable design tools and decision support and databases
39	Provision of technical support
40	Government procurement by the administration
41	Encouragement of public procurement programmes

3.3. Survey design and implementation

The third phase of the methodology consisted of the design and execution of the survey. The questionnaire's design aimed at capturing the diversity of stakeholder opinions, achieve a high degree of reliability, allow stakeholder participation, avoid the prominence of one or more experts over others, ensure balanced participation and sought to form a criterion with a high level of objectivity. To this end, two steps were established:

Step I (preliminary study). A consistency test of the questionnaire was carried out with several items. The purpose of this test was to determine the coherence and usefulness of the items to identify and individually assess the drivers; to analyse the clarity, comprehensibility and objectivity of the drivers proposed; and to gather opinions from stakeholders on other possible interesting drivers that should be added to contribute to the research objective. Thus, the questionnaire test was designed with a 5–point Lickert–type linguistic scale, ranging from total disagreement (1) to total agreement (5). Besides this, an open response option was left open. However, these survey results' relevance was not so much the scores obtained in each item, but the generation of useful information to direct a massive survey to a broader sample. Thus, for the consistency test's execution, interviews were conducted with a selection of respondents from each stakeholder identified. The interviews, each lasting approximately 30 minutes, were conducted by telephone. A total of 40 people was interviewed in this first stage.

Step II. Once the survey consistency test had been examined, suitability adjustments were made to obtain the final survey text. The final questionnaire sent to all respondents was structured in three parts. The first part described the objectives of the questionnaire. The second part recorded the credentials of the stakeholders, including personal, professional and educational details. The third part consisted of several sections, with each section representing each category of driver. Thus, the respondent was asked to mark on a Likert scale from 1 to 5, where 1 = "Strongly disagree" and 5 = "Strongly agree" his or her degree of agreement or disagreement with the implementation of the different drivers for the promotion of sustainable building and retrofitting in dwellings. A ‘1’ meant that the respondent thought that the driver was not helpful in promoting sustainable building, while a 5 meant that the driver was considered valid. The respondent was also given the option of marking the questions' incomprehensibility and a blank space was provided for expanding his or her opinion. Finally, the online survey was sent out in masse to stakeholders; a total of 229 responses were received (Table 16).

3.4. Statistical instrument

Once the survey had been carried out, we performed a quantitative analysis of the data obtained. On the one hand, we performed a descriptive analysis of the respondents' total responses and the responses by driver category, regardless of their profile and previous knowledge of the subject. The following variables were used for this purpose:

- n, number of respondents who indicated this answer,
- p, percentage of the total number of possible respondents who gave this answer,

- a_D, the average score for each item, with 5 points for the highest degree of agreement and 1 for the highest degree of disagreement,

- a_C, the average score per category, with 5 points for the highest degree of agreement and 1 for the highest disagreement.

On the other hand, the dispersion of the data was measured between each driver's responses and between the average scores of each category of drivers. For this purpose, the standard deviation (SD) and the Pearsons Coefficient of Variation were used (Equation 9). The SD is a commonly used measure of variation and is defined as follows (Mendenhall & Sincich, 2016):

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \ (9)$$

where y_i is any measure of the set, is the arithmetic mean of the sample, and n is the sample size. The lower the SD, the higher the significance of the results. Pearson's Coefficient of Variation (CV) (Equation 10) allowed us to compare the dispersions of two different distributions, provided that their means were positive; it is calculated as:

$$CV = \frac{SD}{\bar{x}} \cdot 100\% \ (10)$$

where SD is the standard deviation, and x¯is the arithmetic mean of the sample. The higher the CV, the greater the degree of dispersion of the data. CV values above 50% are already indicative of high dispersion (Pardo et al., 2009).

4. Analysis of results

Following the established methodology, this section presents (i) a quantitative analysis of the responses of all drivers and (ii) a quantitative analysis for each driver category.

4.1. Quantitative analysis of the set of all drivers

According to the responses of the 229 respondents (Table 21), an average of 32% of the stakeholders strongly agreed with the inclusion of drivers for the promotion of sustainability in buildings. However, 5% of the respondents would disagree with the idea of incentives. It is noteworthy that out of the total number of responses, only 2% did not understand the question, which corroborates the comprehensible and transparent character of the survey text. However, an average of 4% of the respondents added other answers to the total number of possible answers. These open answers reflect the concern of the respondents about the increase of other types of taxes; about the detriment of public systems due to the decrease in tax collection; about the environmental impact of the possibility of an increase in buildability or change of use; or about how a building will be assessed and certified as being truly sustainable.

On the other hand, the total average of the scores given to the 41 drivers was 3.62 (5 being the degree of total agreement and 1 the degree of total disagreement), which indicates that the stakeholders would agree with drivers' implementation. Driver number 3 (Figure 43) which refers to the implementation of deductions and rebates in the Urban Property Tax

(IBI), stands out as the one with the highest average (ad=4.43) and the lowest standard deviation (SDd=0.93). This is followed by driver 9, which refers to the Tax on constructions, installations and works, with an average score a=4.40 and SD=0.94. These results indicate a high degree of consensus among respondents regarding the implementation of these drivers. However, drivers 23 (reduction of development charges), 36 (increase in the level of buildability) and 21 (reduction of charges for opening of coves and ditches), which refer to particular issues in the building process and to the increase in the level of buildability, are the ones with the lowest average score (a) and highest SD (a= 2.66, 2.77 and 2.77 and SD=1.62, 1.61 and 1.47 SD, respectively). There is, therefore, a very low degree of consensus among respondents in the refusal to implement these drivers.

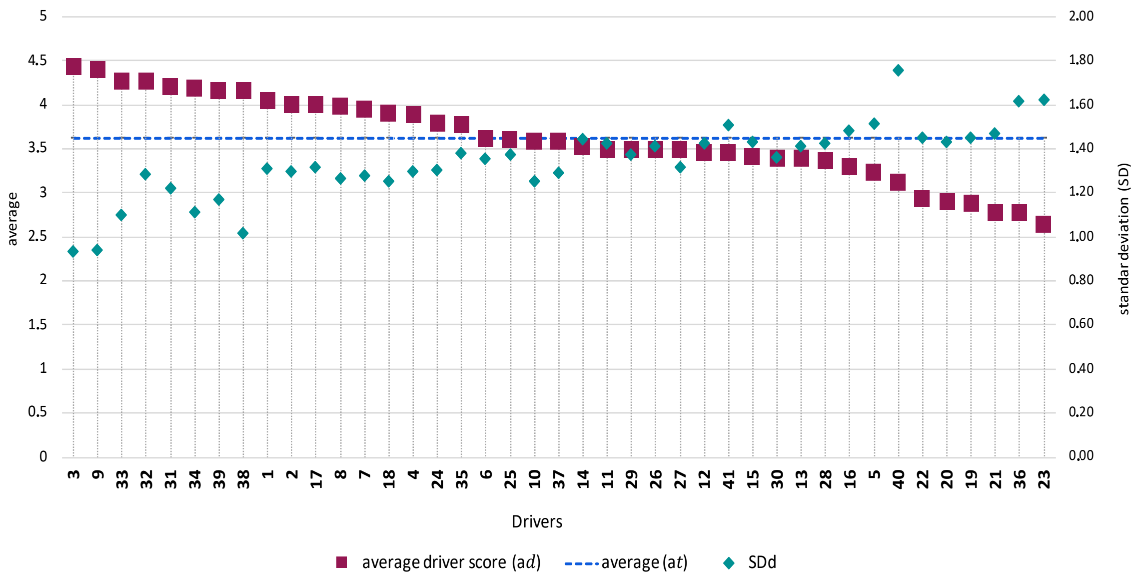


Figure 43. Average scores per driver (ad) and standard deviation of each driver (SD_d).

On the other hand, if we analyse the data from the point of view of those drivers that have obtained a more significant number of responses with "Strong agreement (5)" or "Strong disagreement (1)" (Figure 44) then driver 32, which refers to the granting of non-refundable subsidies, is the one that has obtained the highest degree of total agreement, with 62% of respondents strongly agreeing with its implementation. On the other hand, driver 19, concerning the reduction of parking fees, is the one with the highest level of disagreement, with 13% of respondents being against its implementation.

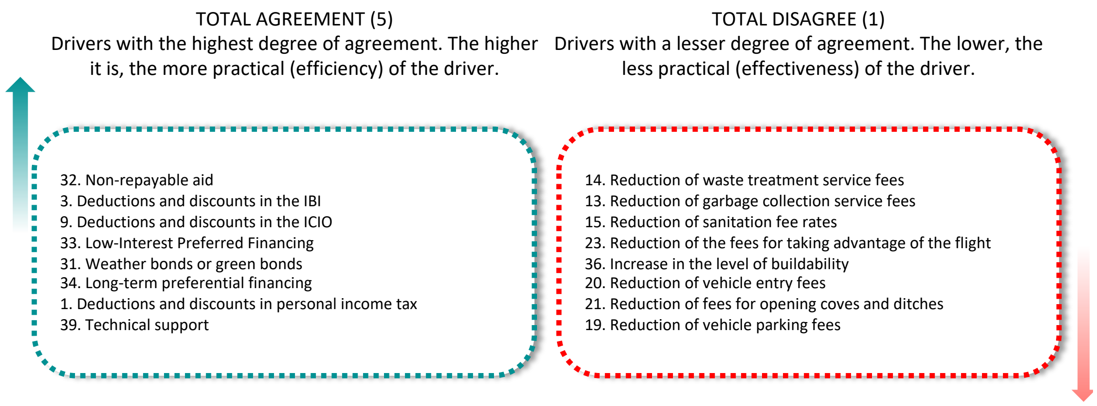


Figure 44. Drivers with the highest number of responses with "Strongly agree (5)" or "Strongly disagree (1)".

Finally, as shown in Figure 45, there is a strong negative relationship between each driver's average score (ad) and the coefficient of variation of each driver (CVd). This indicates that those drivers with the lowest average scores coincide with the highest coefficients of variance. This denotes more significant variability among the responses and, thus, a lower degree of consensus.

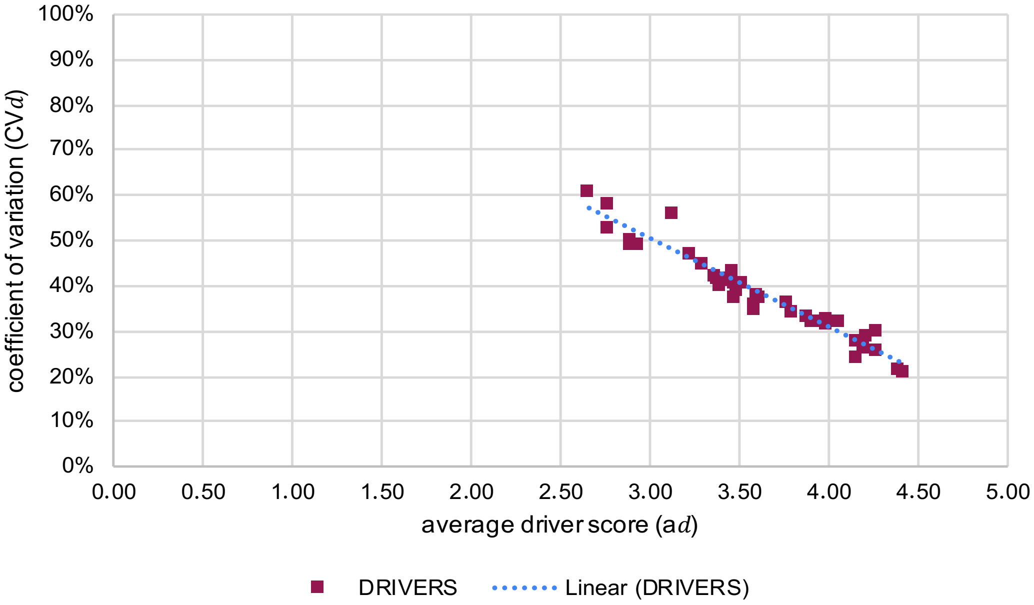


Figure 45. Ratio of average driver score (ad) to coefficient of variance (CVd).

4.2. Analysis of results by driver category

The individual results of the three types of drivers considered (fiscal, financial and government intervention) are analysed below.

4.2.1. Fiscal drivers

In the case of the fiscal driver's category, as shown in Table 22, an average of 29% of respondents strongly agree with the inclusion of tax incentives to promote sustainability in buildings. However, an average of 5% of stakeholders would strongly disagree with implementing drivers to promote sustainability criteria. Of the respondents, only an average of 2% did not understand the questions and 4% had doubts about the implementation of tax and fee reductions and rebates. They questioned whether the tax reduction will only affect high-income earners, how the correct implementation of sustainability criteria will be evaluated, and what type of government bodies will standardise, manage, and execute the drivers' correct implementation. Driver 3 (IBI deductions and rebates) stands out as the driver with the highest degree of agreement, with 46% of respondents strongly agreeing with its implementation. On the other hand, driver 19 (reduction of vehicle parking fees) is the driver with the highest disagreement level, with 13% of respondents in total disagreement.

Table 23. Statistical measures of stakeholder responses per driver category.

	categorie	**(5)**	**(4)**	**(3)**	**(2)**	**(1)**	**(a)**	**(b)**	**Statistical measures**		
		p	p	p	p	p	p	p	a	SD	CV
	fiscal	29%	32%	18%	8%	5%	2%	5%	3.55	0.45	13%
average	financial	50%	35%	7%	2%	2%	1%	3%	4.15	0.21	5%
	gubernamental	30%	35%	14%	8%	4%	4%	4%	3.42	0.56	16%
Average total		32%	33%	16%	7%	5%	2%	4%	3.63	1.30	37%

Strongly Agree (5); Agree (4) ;Indifferent (3); Disagree (2); Strongly Disagree (1); Other (a)I do not understand the question (b)

In Figure 46, it is observed that the average score given to the 30 fiscal drivers is ac= 3.55, with an SDc=0.45. This implies that stakeholders advocate for the establishment of fiscal drivers. Only 5 drivers are below an average of 3 points: 22 (reduction of road user charges), 20 (reduction of vehicle entry charges), 19 (reduction of vehicle parking charges), 21 (reduction of road user charges) and 23 (reduction of road user charges). Drivers 3 (IBI deductions and rebates) and 23 (reduction of taxes for air traffic use) are the drivers with the highest and lowest average scores, respectively. Finally, it is worth noting that the drivers with the lowest average scores coincide with the highest standard deviations and the lowest degree of consensus (Table 22).

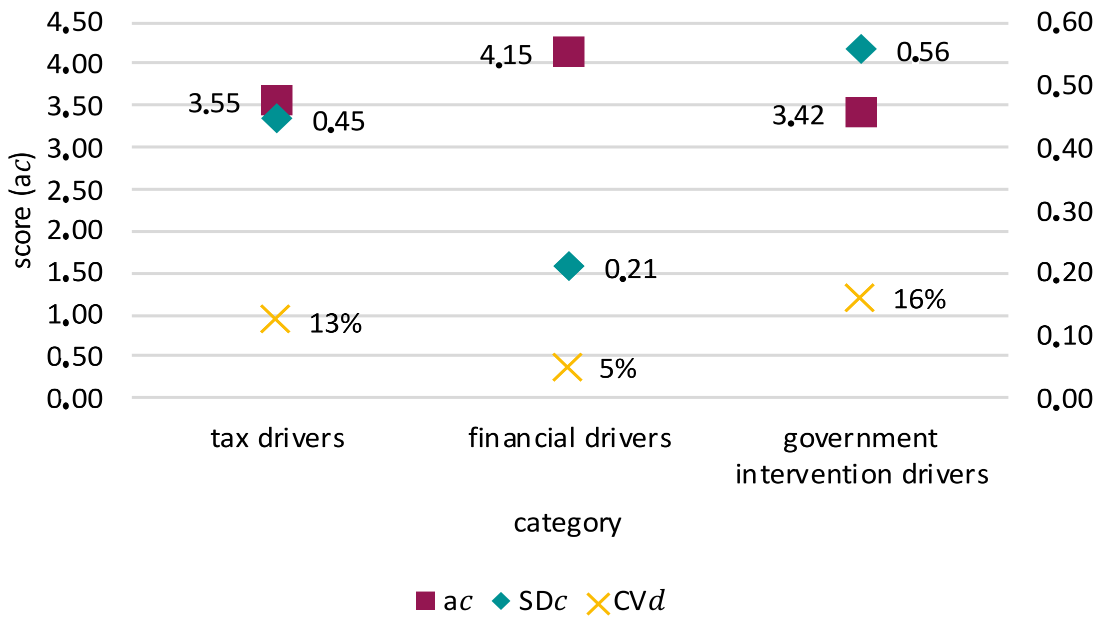


Figure 46. *Average scores per category (ac), standard deviation per category (SDc) and coefficient of variation per category (CVc).*

4.2.2. Financial drivers

In the case of the financial driver's category, as shown in Table 22, an average of 50% of the 229 respondents strongly agree with the inclusion of financial drivers for the promotion of sustainability in buildings; only an average of 2% of the stakeholders would strongly disagree with the idea of implementing financial drivers. It is noteworthy that out of the total number of respondents, only 1% did not understand the questions. However, an average of 3% of stakeholders expressed doubts about the implementation of drivers.

In Figure 46, it is observed that the average score given to the fiscal driver's category is a_c=4.15, with an SD_c=0.21, indicating that stakeholders would agree with the implementation of financial drivers. No drivers presented an average of 3 points. Driver number 33, referring to the granting of preferential low-interest financing, stands out as the driver with the highest average and lowest standard deviation, SD_d=1.10, followed by driver 32 with an average score of a_d=4.27 and SD_d=X, referring to the granting of non-repayable grants, which indicates a high degree of consensus among the respondents. However, driver 35 (financing of public services) has the lowest score, with an average score of a_d=3.77, and the highest standard deviation, SD_d=1.37. These results show a more significant variability among the responses and a lower degree of consensus. Finally, as with the fiscal drivers, the higher the average score, the lower the standard deviation, indicating a high consensus among stakeholders.

4.2.3. Drivers on government interventions

In the case of government intervention drivers, as shown in Table 22, an average of 30% of respondents strongly agree with the inclusion of government intervention drivers. However, an average of 4% of stakeholders would strongly disagree with implementing government intervention drivers, do not understand the questions or give different answers to the ones envisaged. In particular, driver 39 (technical support) stands out as the driver with the highest agreement level, with 46% of respondents strongly agreeing with its implementation. On the other hand, driver 36 (increase in buildability) is the one with the highest level of disagreement, with 10% of respondents strongly disagreeing with the increase in buildability as an instrument to promote sustainability.

In Figure 46, it can be observed that the overall average of the scores given to the government intervention driver category is ac=3.42 and an SDc=0.56. This denotes a consensus among stakeholders regarding the implementation of this category of drivers. Driver number 39 (proportion of technical support) stands out as the driver with the highest average score and the lowest standard deviation obtained (SDd=1.10). On the other hand, driver 36 (increase in buildability) has the lowest score, with an average of ad=2.77, and SDd=1.61. This denotes more significant variability among the responses and, therefore, a lower degree of consensus. Finally, as with the fiscal drivers, the higher the average score, the lower the standard deviation. This denotes a high degree of consensus among stakeholders.

5. Discussion

The analysis of the results in the previous section supports the fact that stakeholders agree with drivers' implementation to promote sustainability criteria in buildings, with a high degree of consensus. However, the less relevant drivers created quite a disparity among respondents.

Financial drivers stand out as the most relevant and with the highest degree of consensus, which shows that financial subsidies can stimulate sustainable building development. In China, local economic fundamentals and subsidy-based incentive policies explain the construction of sustainable buildings (Zou et al., 2017). The European Investment Bank is also actively financing housing affordability and sustainability. Similarly, banks favour sustainable buildings, whose cost amortisation over the life cycle of the building would ensure more manageable repayment of loans. Sustainable housing, therefore, offers life−cycle cost savings to owners and occupants. Besides this, they are rented or sold faster, which offers the potential for higher profits (Hwang & Ng, 2013).

Therefore, our results are in line with and build on previous research findings and analysis of experiences in other countries. Furthermore, these results suggest that, in the respondents' opinion, the financial effort to implement sustainability criteria in housing could be compensated by the returns derived from measures adopted by both governments and private entities. Therefore, our results support the interest in deepening the relationship between investment in financial drivers and the benefits derived from their effects as a basis for developing governance models aimed at promoting sustainable building.

Concerning fiscal drivers, the inclusion of deductions and rebates in the Urban Property Tax (IBI) is of particular relevance. This type of driver is already being implemented in some regions of Spain, establishing up to a 50% deduction in the number of investments that improve housing quality and sustainability. However, these investments are restricted to particular housing actions, focusing on energy efficiency aspects and forgetting the wide range of sustainable aspects of the building. However, the drivers that refer to specific aspects of the building process (i.e. occupation of public roads, trench openings or façade overhangs etc.) are the least relevant. This may be because these drivers refer to particular parts of the building, such as façade overhangs or ground trenches, which are either not considered relevant or are not considered part of the building's sustainability. However, from a fiscal point of view, they do count for tax purposes. In any case, our results represent an advance on previous research findings because we have identified government decisions on specific taxes as instruments to stimulate sustainable building.

Similarly, the drivers with the lowest degree of agreement among stakeholders are those related to government interventions. Thus, the driver relating to the increase in buildability creates controversy among respondents. Respondents expressed doubts about the increased environmental impact that this could have and that it would not compensate for the other sustainable aspects. However, studies such as Kong and He (Kong & He, 2021) and Shi and Liu (Shi et al., 2014) show that floor area ratio rewards can also motivate developers to pursue innovations in green building technology. Moreover, such drivers are already being implemented in some regions (e.g. the Canary Islands) in hotel buildings where each tranche of 20% of the annual energy expenditure generated by renewable means will entitle a 0.1m^2c/m^2 increase in floor area over the standard (Canarias, 2013).

As an advance on the findings of previous research, it is worth noting that in the case of government drivers, our results reveal how controversial this issue is and the doubts that all the agents involved have. This opens up several research lines on how particular sustainable actions would be and how they could be balanced within the complex interplay of the concept of sustainability and resilience, the circular economy, and adaptation to climate change in buildings. This approach raises the question of whether specific criteria should be prioritised over others or whether, on the contrary, the success of the new paradigm of the building stock is based on equity between all environmental, economic and social stakeholders.

Finally, it is worth noting the respondents' concerns about how compliance with sustainability criteria will be certified. This is where the concept of the Sustainable Building Assessment Method comes in. These instruments are based on criteria that provide quantitative and qualitative performance indicators from an environmental, economic and social point of view (Carmen Díaz-López et al., 2019; López et al., 2019). However, the voluntary nature of these instruments (Haapio & Viitaniemi, 2008) conditions the potential of these tools as a precursor to sustainable building development (López et al., 2019).

6. Conclusions

Our empirical results are novel due to the high number of incentives analysed, covering the entire building life cycle and addressing all aspects of sustainability (environmental, economic and social) by studying the opinions of a wide variety of stakeholders. Thus, the findings and methodology used can be interesting for governments of countries interested in implementing policies to promote sustainable building due to our results' extrapolated nature.

The findings obtained show that stakeholders, in general, strongly agree with the implementation of governmental drivers as instruments to stimulate sustainability in the construction, renovation and use of dwellings. The most highly-rated drivers are those considered to be the most effective in driving sustainable building and can help guide the definition of public policies on sustainable housing.

In the opinion of the stakeholders surveyed, the most valuable drivers to boost sustainability in housing are financial drivers, followed by fiscal drivers and government interventions. This reveals the opportunity and interest by governments to exercise their legal powers to implement measures aimed at implementing these three types of instruments (financial, fiscal and government interventions).

For the financial drivers, our results show that the most effective government measures would be to provide non–repayable subsidies, facilitate preferential low-interest financing for sustainable homebuyers, and provide climate bonds for homeowners and non-homeowners.

In fiscal drivers, government policies should mainly be directed towards legally regulating rebates and deductions in property tax, building and construction tax, income tax (buyers), corporate tax, value-added tax (construction companies and developers), and fees for habitability and first occupancy licences. These policies may involve decisions at different government levels, such as local governments and central governments, which should act in a coordinated manner in their measures to promote sustainable building.

On the other hand, in terms of government interventions, public policies should be based, as a matter of priority, on technical support mechanisms, implementation of housing design support tools, facilitating access to databases and providing subsidies to finance public services.

These findings show the need for governments to put legal, fiscal, technical and social measures in place to promote sustainability in housing construction, renovation and use, using a comprehensive and integrated approach to balance the economic, environmental and social aspects of housing provision.

In parallel, our results suggest that the effectiveness of the measures require coordinated planning between the policies to be adopted at different levels of government (central government, regional governments and local governments). In this sense, it could be interesting for national governments to regulate possible fiscal and financial incentives and, on that basis, for regional and local governments to implement specific drivers adapted to the peculiarities of the socio-economic context of each territory. More specifically, fiscal policies for sustainable building should focus on direct and indirect taxes rather than fees.

Finally, our results also support the idea that sustainable building could be promoted through other governmental measures aimed at increasing the visibility of its benefits among citizens and at improving the transparency and reliability of the drivers to be applied, such as: analysis and dissemination of the economic effects derived from tax rebates, study and publication of the environmental impact derived from the increase of buildability and change of use, and definition of procedures and methodologies to assess and certify the sustainability of buildings.

CONCLUSIONES

Las aportaciones más importantes que se han obtenido a partir de este trabajo se han agrupado en tres apartados coincidentes con los objetivos secundarios establecidos en esta memoria:

(i) Analizar la evolución científica de la edificación sostenible y de los SBAMs.

(ii) Estudiar y comparar los SBAMs existentes.

(iii) Identificar y sentar las bases de estrategias dirigidas a facilitar e impulsar la implantación de SBAMs.

En relación con el análisis de la evolución científica de la edificación sostenible y de sus métodos de evaluación:

- Los campos de investigación sobre los SBAMs y la edificación sostenible se han desarrollado en paralelo, siendo amplios, complejos y fragmentados, debido a la gran diversidad de disciplinas y enfoques involucrados.

- La investigación en estos campos se inició en el año 1975 y sigue a fecha de hoy en evolución, estando marcada por temas relevantes como la eficiencia energética, el análisis del ciclo de vida, las energías renovables, o más recientemente la necesidad de adaptar la edificación al cambio climático y los principios de economía circular.

En relación con el estudio comparativo de los métodos de evaluación de edificación sostenible existentes:

- Los SBAMs han jugado un papel trascendental en el desarrollo de la edificación sostenible mediante la sensibilización de las partes interesadas, y se han clasificado en tres categorías: Sistemas, Estándares y Herramientas. Recientemente se ha incorporado un nuevo método, Level(s), basado en los anteriores y que abarcar un concepto más amplio de edificación sostenible.

- El conjunto de SBAMs analizados han mostrado que las fases de ciclo de vida incluidas en la evaluación, los aspectos de sostenibilidad, las categorías y el tipo y estado del proyecto evaluado difieren según el país y la fecha de lanzamiento. Además, la energía y la calidad ambiental interior han sido los aspectos ambientales de la sostenibilidad que se han identificado como más influyentes y de fácil acceso, frente a los aspectos sociales y económicos, de más reciente incorporación.

- El único método que incluía la adaptación de los edificios a los cambios climáticos futuros a lo largo de todo el ciclo de vida, con base en los principios básicos de la economía circular, en el momento de estudio, ha sido Level(s), por lo que se ha identificado como el método más completo.

Dado el alcance de Level(s), así como la intensa labor que se está desarrollando desde la Comisión Europea para impulsar su uso, el análisis y definición de estrategias para la implantación de SBAMs se ha centrado en este método. En relación con éste se ha concluido lo siguiente:

- Los expertos consultados han valorado positivamente Level(s), destacando del mismo su respuesta a la necesidad de adaptar los edificios al cambio climático, lenguaje de referencia estándar y uso en múltiples situaciones.
- Entre las barreras identificadas, y que pueden afectar su desarrollo, se destacan su complejidad de uso, falta de autosuficiencia, dependencia de los criterios utilizados en cada evaluación, así como la necesidad de establecer regulaciones e implementar incentivos que faciliten el desarrollo de edificación sostenible.
- Entre las estrategias definidas para facilitar la implantación de Level(s) se destaca la necesidad de identificar los efectos del cambio climático sobre la edificación así como la identificación de incentivos para la implantación de edificación sostenible.
- En cuanto a la necesidad de identificar los efectos del cambio climático, se ha estudiado el caso de España, concluyendo los siguiente:
    - Se han constatado que los efectos del cambio climático en la España peninsular que están provocando que en más del 80% de las ciudades se diseñen y construyan edificios con un CTE que no tiene en cuenta la realidad climática actual, lo que está afectando significativamente al rendimiento energético de los edificios y

pone de manifiesto la necesidad de revisar la zonificación climática en el país.

- Se espera que dichos cambios se sigan generando de manera que para el año 2085, y bajo las previsiones registradas en los escenarios RCP 4.5 y RCP 8.5, prácticamente todas las ciudades de la España peninsular variarán su zona climática por una más cálida, lo que provocará una disminución de la demanda energética de calefacción de las viviendas, y un aumento de las necesidades de refrigeración.

- La metodología definida en este trabajo puede ser utilizada como referencia para el desarrollo de nuevas zonas climáticas y recomendaciones reglamentos, planes o estrategias de construcción en otras regiones donde la actual falta de normas o regulaciones sobre la adaptación de los edificios al cambio climático da lugar a un *stock* de construcción obsoleto, que es incapaz de hacer frente al dinamismo climático que ya se está produciendo. Esto que ayudará a conservar las correctas condiciones térmicas en el futuro, en el marco de una edificación resiliente.

En cuanto al desarrollo de incentivos para la implantación de edificación sostenible, aplicado en este estudio en España, se han obtenido las siguientes conclusiones:

- Las partes interesadas en el sector de la edificación están muy de acuerdo con la implantación de incentivos como instrumentos estimulantes de la sostenibilidad en la edificación, siendo los financieros los más valorados, seguidos de los fiscales, ocupando el tercer lugar los de intervenciones gubernamentales.
- De entre los drivers financieros, los que se han identificado como más eficaces han sido la concesión de subvenciones a fondo perdido, la financiación preferente de bajo interés y la concesión de bonos clima.
- En el caso de los drivers fiscales y de intervenciones gubernamentales, estos pueden implicar decisiones en diferentes niveles de gobierno, local, autonómico y central. En materia de intervenciones gubernamentales, las políticas públicas deberían basarse, prioritariamente, en mecanismos de apoyo técnico, implantación de herramientas de apoyo al diseño de viviendas y facilitar el acceso a bases de datos y conceder subvenciones para financiar servicios públicos.

CONCLUSIONS

The most significant contributions obtained from this work have been grouped into three sections that coincide with the secondary objectives established in this report:

(i) To analyse the scientific evolution of sustainable building and SBAMs.

(ii) To study and compare existing SBAMs.

(iii) To identify and lay the foundations for strategies to facilitate and promote the implementation of SBAMs.

Concerning the analysis of the scientific evolution of sustainable building and its assessment methods:

- The research fields on SBAMs and sustainable building have developed in parallel, being broad, complex and fragmented, due to the great diversity of disciplines and approaches involved.

- Research in these fields started in 1975 and is still evolving, being marked by relevant topics such as energy efficiency, life cycle analysis, renewable energies, or more recently, the need to adapt buildings to climate change and the principles of the circular economy.

Concerning the comparative study of existing SBAMs:

- SBAMs have played a significant role in developing sustainable building by raising stakeholder awareness and classified it into Systems, Standards and Tools. A new method, Level(s), has recently been added, which builds on the previous ones and encompasses a broader concept of sustainable building.

- The set of SBAMs analysed have shown that the life cycle phases included in the assessment, the sustainability aspects, the categories, and the type and status of the assessed project differ according to country and launch date. Furthermore, energy and indoor environmental quality have been identified as the most influential and easily accessible environmental aspects of sustainability than the more recently incorporated social and economic aspects.

- The only method that included the adaptation of buildings to future climate change throughout the whole life cycle, based on the basic principles of the circular economy, at the time of the study was Level(s) and was therefore identified as the most comprehensive method.

Given the scope of Level(s) and the intense work being carried out by the EUto promote its use, the analysis and definition of strategies for the implementation of SBAMs have focused on this method. Concerning this method, the following conclusions have been reached:

- The experts consulted have positively assessed Level(s), highlighting its response to the need to adapt buildings to climate change, its standard reference language and its use in multiple situations.
- Among the barriers identified, which may affect its development, are its complexity of use, lack of self-sufficiency, dependence on the criteria used in each assessment, and the need to establish regulations and implement incentives to facilitate the development of the sustainable building.
- Among the strategies defined to facilitate the implementation of Level(s), the need to identify the effects of climate change on building and the identification of incentives for the implementation of sustainable building are highlighted.
- Regarding the need to identify the effects of climate change, the case of Spain has been studied, and the following conclusions have been reached:
    - It has been found that the effects of climate change in peninsular Spain are causing more than 80% of cities to design and construct buildings with a CTE that does not consider the current climatic reality, which is significantly affecting the energy performance of buildings and highlights the need to review climate zoning in the country.
    - It is expected that these changes will continue to be generated in such a way that by 2085, and under the forecasts recorded in the

RCP 4.5 and RCP 8.5 scenarios, practically all the cities in mainland Spain will change their climate zone to a warmer one, which will lead to a decrease in the heating energy demand of dwellings and an increase in cooling needs.

  - The methodology defined in this work can be used as a reference for the development of new climate zones and recommendations for building regulations, plans or strategies in other regions where the current lack of standards or regulations on the adaptation of buildings to climate change results in an obsolete building stock, which is unable to cope with the climate dynamism that is already occurring. It will help preserve the correct thermal conditions in the future in the framework of a resilient building.

- Regarding the development of incentives for the implementation of sustainable building, applied in this study in Spain, the following conclusions have been obtained:

  - Stakeholders in the building sector strongly agree with implementing incentives as instruments stimulating sustainability in building, with financial incentives being the most valued, followed by fiscal incentives, with governmental interventions coming in third place.

  - Among the financial drivers, those identified as most effective were granting non-repayable subsidies, preferential low-interest financing and the granting of climate bonds.

- In the case of fiscal drivers and government interventions, these may involve decisions at different government, local, regional and central levels. In terms of government interventions, public policies should be based, as a priority, on technical support mechanisms, implementation of tools to support housing design and facilitate access to databases and grant subsidies to finance public services.

LÍNEAS FUTURAS DE INVESTIGACIÓN

En el desarrollo de este trabajo, han surgido algunos aspectos derivados del mismo que necesitan de un análisis más detallado, por lo que se proponen a continuación las siguientes futuras líneas de investigación:

- Analizar la adaptación de indicadores de Level(s) al contexto de cada país. Al ser un lenguaje de referencia común para toda Europa, se puede llegar a un consenso entre todos los países europeos, permitiendo a cada país adoptar los criterios de sus condiciones constructivas y socioeconómicas.

- Identificar, analizar y evaluar a nivel Europeo el efecto de cambio climático y la isla de calor urbano sobre la edificación y el entorno construido; así como indicadores de evaluación de resiliencia en edificación y el entorno construido.

- Diseñar estrategias pasivas de soluciones constructivas adaptadas al cambio climático, dentro del marco de la economía circular.

- Diseñar estrategias de desarrollo, implantación y evaluación de edificación sostenible, adaptada al cambio climático y resiliente, dentro del marco de la economía circular.

- Extrapolar y adaptar los indicadores de Level(s) a otros campos de investigación, como las infraestructuras líneas y el urbanismo.

- Analizar y evaluar la sostenibilidad, la adaptación al cambio climático, la circularidad y la resilencia de la arquitectura vernácula.

FUTURE LINES OF RESEARCH

In the development of this work, some aspects have arisen that require more detailed analysis, for which reason the following future lines of research are proposed below:

- Analyse the adaptation of Level(s) indicators to the context of each country. As it is a common reference language for the whole of Europe, a consensus can be reached between all European countries, allowing each country to adopt the criteria of its constructive and socio-economic conditions
- Identify, analyse and evaluate the effect of climate change and the urban heat island on buildings and the built environment and indicators for assessing resilience in buildings and the built environment at the European level.
- Design passive strategies for building solutions adapted to climate change within the framework of the circular economy.
- Design strategies for developing, implementing, and evaluating sustainable, climate change-adapted and resilient building within the circular economy framework.
- Extrapolate and adapt Level(s) indicators to other research fields, such as linear infrastructures and urban planning.
- Analyse and evaluate the sustainability, adaptation to climate change, circularity and resilience of vernacular architecture.

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