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Análisis del Ciclo de Vida en la construcción: evaluación de las etapas incorporadas de elementos de la vivienda y de su entorno urbano.

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Barcelona, España. A 23 de septiembre de 2019.

TESIS DOCTORAL

Análisis del Ciclo de Vida en la construcción: evaluación de las etapas incorporadas de elementos de la vivienda y de su entorno urbano.

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TESIS PRESENTADA PARA OBTENER EL TÍTULO DE DOCTORA POR LA UNIVERSIDAD POLITÉCNICA DE CATALUÑA

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DEDICADO A:

***Héctor**, ha pasado toda una vida frente a nosotros durante estos años,*

ha sido tan duro como hermoso, hemos sido el mejor equipo,

esto es tan tuyo como mío.

***Bauti**, simplemente porque eres mi todo.*

***Pedrito**, lo más difícil de estar lejos,*

fue perderme cinco años de tu vida.

Mi futura generación:

Juanito, Guillermo, Santi, Helenita, Renata, Marita, Romina,

María Paula, Regina y Luciana.

…pero de eso trata la vida, de equivocarse y seguir, de caer y levantarse, de voltear hacia atrás y ver todas las piedras que hemos superado. De ver hacia atrás y no detenerse demasiado. La vida es eso.

(Diana Gámez)

Resumen

El sector de la construcción tiene el potencial de contribuir en el logro de algunos de los objetivos más importantes del desarrollo sostenible, como el combate al cambio climático, la defensa del medio ambiente o el diseño de las ciudades. Este sector es responsable de generar altas tasas de emisiones de gases de efecto invernadero y de residuos de construcción y demolición, además del consumo desmesurado de recursos abióticos y energía no renovables. En la búsqueda de mitigar estas consecuencias negativas se han desarrollado herramientas que permiten gestionar estos impactos ambientales, una de ellas es el análisis del ciclo de vida (ACV). Esta tesis tiene como objetivo evaluar la aplicabilidad del ACV en el sector de la construcción; en específico, evaluar los impactos ambientales incorporados del ciclo de vida en la edificación de vivienda y de su entorno urbano. En esta tesis se evaluaron: i) veinte muros exteriores y se establecieron las configuraciones más adecuadas para el ambiente, así como un sistema de ecuaciones que definió su comportamiento; ii) dieciocho calles residenciales con alternativas que priorizaron el flujo no motorizado y su influencia en los impactos ambientales (ambos estudios mediante un ACV de la cuna a la entrega) y; iii) seis tipologías de vivienda, donde se variaron los materiales utilizados en los muros y las ventanas (mediante un análisis de la cuna a la tumba). Para este último caso, se abordaron también los retos ambientales del sector residencial en México. Las bases de datos utilizadas fueron BEDEC, CYPE Latam (cuantificación de los materiales) y ecoinvent (inventario de ciclo de vida). Los métodos de impacto ambiental utilizados fueron CML 2001, Ecoindicador 99, IPCC 2013 y CED. En esta tesis se corroboró que el ACV es una metodología aplicable en la construcción, la cual con la constante actualización de la normativa ha permitido la obtención de resultados cada vez más globales y transparentes, lo cual ha hecho posible la expansión del ACV a nuevas geografías. Además, se encontró que la etapa de mayor contribución al detrimento ambiental es la de producto o las que involucran un producto (como el mantenimiento y el reemplazo), mientras que las etapas referentes a los procesos tienen una menor contribución, de éstas el transporte fue la más relevante. Los elementos con el mayor potencial de daño ambiental fueron las aceras de granito, las ventanas de aluminio, los aislamientos térmicos de XPS y el galvanizado de la placa de yeso laminado. Se corroboró que los materiales más típicos de construcción, como los elaborados con cemento (hormigón, mortero, entre otros), las piezas cerámicas de arcilla o el acero, son altos generadores de gases de efecto invernadero y consumidores de energía. Por otra parte, se encontró que dar prioridad a la escala humana en el diseño de las calles reduce los impactos ambientales. La elaboración de ACV de la cuna a la entrega (parciales) permitió establecer un mayor número de escenarios, compararlos y encontrar la alternativa más ambientalmente correcta; mientras que la elaboración de ACV de la cuna a la tumba, permitió conocer el comportamiento ambiental de todo el ciclo de vida; es decir, los impactos totales de la vivienda y detectar donde se encontraban las oportunidades de mejora (aunque esto significó la limitación de los escenarios por la complejidad del estudio). Los hallazgos de esta tesis permitieron concluir que el ACV tiene un potencial importante en la consecución de esquemas de evolución sostenible, por lo que su aplicabilidad en el sector de la

construcción es factible y recomendado (en países emergentes o en vías de desarrollo resulta idóneo). Por último, se concluye que el ACV es una herramienta que puede contribuir a la obtención de los objetivos del desarrollo sostenible y que es esencial para hacer frente a los cambios acelerados causados por el daño ambiental que genera el sector de la construcción.

Abstract

The construction sector has the potential to contribute to the achievement of essential objectives of sustainable development, such as the fight against climate change, the defense of the environment or the design of cities. This sector is responsible for generating high rates of greenhouse gas emissions and construction and demolition waste, in addition to the excessive consumption of non-renewable abiotic and energy resources. In the search to mitigate these negative consequences, tools have been developed that allow these environmental impacts to be managed, one of them is the life cycle analysis (LCA). This thesis aims to assess the applicability of LCA in the construction sector. Specifically, evaluate the embodied environmental impacts in the life cycle in the housing construction and its urban environment. In this thesis were evaluated i) twenty exterior walls and the most environmentally appropriate configurations were established, as well as a system of equations that defined their environmental behavior, ii) eighteen residential streets with alternatives that prioritized non-motorized flow, and their influence on environmental impacts (both studies through an LCA from the cradle to handover) and iii) six types of housing, where the materials used in the walls and windows were varied (through an analysis of the cradle to the grave). For the latter case, the environmental challenges of the residential sector in Mexico were also addressed. The databases used were BEDEC, CYPE Latam (quantification of materials) and ecoinvent (life cycle inventory). The environmental impact methods used were CML 2001, Ecoindicator 99, IPCC 2013, and CED. In this thesis it was corroborated that LCA is a methodology applicable in construction which, with the constant updating of the regulations, has allowed the obtaining of increasingly global and transparent results, allowing the expansion of LCA to new geographies. Also, it was found that the stage of the greatest contribution to the environmental detriment is that of the product, or those that involve a product (such as maintenance and replacement), while the stages related to the processes have a lower contribution, of these the transport was the most relevant. The elements with the highest potential for environmental damage were granite sidewalks, aluminum windows, XPS thermal insulation, and galvanized laminated plasterboard. It was confirmed that the most typical construction materials, such as those made with cement (concrete, mortar, among others), ceramic pieces of clay or steel, are high generators of greenhouse gases and energy consumers. On the other hand, it was found that prioritizing the human scale in street design reduces environmental impacts. The development of LCA from the cradle to handover (partial) allowed to establish a higher number of scenarios, compare them and find the most environmentally correct alternative; while the development of LCA from cradle to grave, allowed to know the environmental behavior of the entire life cycle; that is, the total impacts of housing and detect where the opportunities for improvement were located (although this meant the limitation of the scenarios due to the complexity of the study). The findings of this thesis allowed us to conclude that LCA has an essential potential in achieving sustainable evolution schemes, so its applicability in the construction sector is feasible and recommended (in emerging or developing countries it is suitable). Finally, it is concluded that LCA is a tool that can contribute

to the achievement of the objectives of sustainable development and that it is essential to cope with the accelerated changes caused by the environmental damage generated by the construction sector.

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ABREVIATURAS RELEVANTES

ACV	Análisis de Ciclo de Vida
GEI	Gases de efecto invernadero
ACCV	Análisis de costo de ciclo de vida
ACV-S	Análisis de ciclo de vida social
ASCV	Análisis de sostenibilidad del ciclo de vida
GCV	Gestión del ciclo de vida
PCV	Pensamiento del ciclo de vida
ICV	Inventario de ciclo de vida
EICV	Evaluación del impacto ambiental
PCG	Potencial de calentamiento global
ARA	Agotamiento de los recursos abióticos
PA	Potencial de acidificación
PE	Potencial de eutrofización
PTH	Potencial de toxicidad humana
EE	Energía incorporada
EO	Energía operativa
A1-A3	Etapas de producto
A1-A5	Etapas del proceso de construcción
A4; C2	Etapas de transporte
B1-B5	Etapas del uso
B2	Etapa de mantenimiento
B4	Etapa de reemplazo
C1-C4	Etapas del final de la vida
ALC	América Latina y el Caribe
XPS	Poliestireno extruido
EPS	Poliestireno expandido

ESTRUCTURA DE LA TESIS

Esta tesis se presenta por modalidad de compendio de publicaciones bajo la normativa del Doctorado de Tecnología de la Arquitectura, Edificación y Urbanismo. Este trabajo consta de cuatro capítulos. En el primero se expone la introducción de la unidad temática de las tesis: el Análisis del Ciclo de Vida (ACV) de los impactos incorporados en el sector de la construcción. El segundo capítulo incluye una breve explicación de lo que se realizó en cada uno de los tres artículos; en este se resaltan las características más importantes del estudio, el estado del arte consultado para su realización y la forma de aplicación de la normativa. En el tercer capítulo se exponen los artículos publicados en el orden cronológico. En el cuarto capítulo se da una discusión global de los resultados y las conclusiones más relevantes de este trabajo. Los artículos que forman parte de este compendio de publicaciones son los siguientes:

1. Gámez-García, D.C., Gómez-Soberón, J.M., Corral-Higuera, R., Saldaña-Márquez, H., Gómez-Soberón, M.C., Arredondo-Rea, S.P. A Cradle to Handover Life Cycle Assessment of External Walls: Choice of Materials and Prognosis of Elements. *Sustainability* **2018,** *10*, 2748. doi:10.3390/su10082748.

   FI: 2.075 (JCR 2017, Q2)
   Número de citas en Scopus: 5

2. Gámez-García, D.C., Saldaña-Márquez, H., Gómez-Soberón, J.M., Corral-Higuera, R. Arredondo-Rea, S.P. Life Cycle Assessment of residential streets from the perspective of favoring the human scale and reducing motorized traffic flow. From cradle to handover approach. *Sustain. Cities Soc.* **2019,** *44*, 332-342, doi:10.1016/j.scs.2018.10.018.

   FI: 3.073 (JCR 2017, Q1)
   Número de citas en Scopus: 5

3. Gámez-García, D.C., Saldaña-Márquez, H., Gómez-Soberón, J.M., Arredondo-Rea, S.P., Gómez-Soberón, M.C., Corral-Higuera, R. Environmental challenges in the residential sector: life cycle assessment of Mexican social housing. *Energies* **2019**, *12*, 2837, doi:10.3390/en12142837.

   FI: 2,676 (JCR 2017, Q2)
   Número de citas en Scopus: 0

Por último, se incluyen como anexos seis artículos más que se produjeron a lo largo de estos años de pertenecer al doctorado (tres de ellos indexados a JCR). Dos de los temas abordados, nacen de investigaciones paralelas a la de ACV en la construcción. La primera es hormigón sostenible y la segunda es sistemas de evaluación de la sostenibilidad. Ambos temas, complementan los estudios y competencias adquiridas en este lapso de tiempo y permiten aproximarse a un concepto más amplio de la sostenibilidad.

4. Gámez-García, D.C., Gómez-Soberón, J.M., Corral-Higuera, R., Almaral-Sánchez, J.L., Gómez-Soberón, M.C., Gómez-Soberón, L.A. LCA as Comparative Tool for Concrete Columns and Glulam Columns. *Journal of Sustainable Architecture and Civil Engineering* **2015**, *11*, 21-31, doi.org/10.5755/j01.sace.11.2.10291

   FI: 79.5 (Copernicus 2015)

5. Gómez-Soberón, J.M., Saldaña-Márquez, H., Gámez-García, D.C., Gómez-Soberón, M.C. Arredondo-Rea, S.P., Corral-Higuera, R. A comparative study of indoor pavements waste generation during construction through simulation tool. *International Journal of Sustainable Energy Development*, **2016**, *5*, 243-251.

   FI: 13.666 (Infonomics Society´s Indexing Citation Board 2016)

6. Gámez-García, D.C., Saldaña-Márquez, H., Gómez-Soberón, J.M., Corral-Higuera, R. Estudio de factibilidad y caracterización de áridos para hormigón estructural. *Ingeniería y Desarrollo* **2017**, *35*, 283-304, doi.org/10.14482/inde.35.2.10162

   FI: 5.88 (Copernicus 2013)

7. Saldaña-Márquez, H., Gómez-Soberón, J.M., Arredondo-Rea, S.P., Gámez-García, D.C., Corral-Higuera, R. Sustainable social housing: The comparison of the Mexican funding program for housing solutions and building sustainability rating systems. *Building and Environment,* **2018**, *133*, 103-122 doi:10.1016/j.buildenv.2018.02.017.

   FI: 4.539 (JCR 2017, Q1)
   Número de citas en Scopus: 12

8. Arredondo-Rea, S.P., Corral-Higuera, R., Gómez-Soberón, J.M., Gámez-García, D.C., Bernal-Camacho, J.M., Rosas-Casarez, C.A., Ungsson-Nieblas, M.J. Durability Parameters of Reinforced Recycled Aggregate Concrete: Case Study. *Applied Sciences* **2019**, *9(4),* 617. doi:10.3390/app9040617.

   FI: 1.855 (JCR 2017, Q3)
   Número de citas en Scopus: 2

9. Saldaña-Márquez, H., Gámez-García, D.C., Gómez-Soberón, J.M., Arredondo-Rea, S.P., Corral-Higuera, R., Gómez-Soberón, M.C. Housing Indicators for Sustainable Cities in Middle-Income Countries through the Residential Urban Environment Recognized using Single-Family Housing Rating Systems. *Sustainability* **2019**, *11(16)*, 4276. doi: 10.3390/su11164276.

   FI: 2.075 (JCR 2017, Q2)
   Número de citas en Scopus: 0

CAPÍTULO 1

INTRODUCCIÓN

1.1. LAS ETAPAS DE LOS IMPACTOS INCORPORADOS

En la década de 1980 la Organización de las Naciones Unidas introdujo el concepto de desarrollo sostenible y lo definió como el "desarrollo que satisface las necesidades del presente sin comprometer la capacidad de las generaciones futuras para satisfacer sus propias necesidades" [1,2]. En este sentido, en 2015 aprobó la Agenda 2030 sobre el Desarrollo Sostenible, la cual establece 17 objetivos que incluyen desde la eliminación de la pobreza hasta el combate del cambio climático, la defensa del medio ambiente o el diseño de nuestras ciudades [2].

El sector de la construcción tiene un elevado potencial de contribuir en el logro o el fracaso de algunos de los objetivos más importantes de la Agenda 2030; ya que es un responsable protagónico del deterioro del medio ambiente, del cual destacan su contribución al cambio climático, así como al desmesurado consumo de recursos abióticos y energías no renovables [3]. Investigaciones previas señalan que este sector utiliza alrededor del 40% de la energía primaria en el mundo y se le atribuyen el 30% de los gases de efecto invernadero (GEI) generados [4,5].

Para que el ámbito de la construcción se lleve a cabo son necesarios un conjunto de industrias y sectores, de los cuales la edificación y el urbanismo desempeñan un rol sobresaliente debido al número de actividades requeridas para su práctica. El estudio de estos dos sectores debería considerarse como inherente, ya que su éxito individual será potenciable si en su diseño y ejecución se consideran parámetros conjuntos.

La edificación es conocida por ser uno de los mayores contribuidores de impactos ambientales en el mundo [6]. Los edificios juegan un rol importante en el consumo de energía y de recursos naturales, así como también en la generación de las emisiones relacionadas a éstos [7]. Tan sólo en Europa alrededor del 40% del total del consumo de energía le corresponde [8]. Además de que produce el 33% de los residuos anuales [9]. En la búsqueda de mitigar estas consecuencias negativas se han desarrollado estudios sobre impactos ambientales o similares. Se tiene registro de que las primeras investigaciones se llevaron a cabo en los años 1960-1970, las cuales tenían como objetivo evaluar y comparar una serie de productos consumibles [10]. A continuación, se introdujo la evaluación de tecnologías y de análisis de flujo de sustancias incursionando en lo que se convertiría en el actual concepto de ACV [11].

El ACV como término se introdujo a partir de 1990 por la Sociedad de Toxicología y Química Ambiental (SETAC) [10,11], la cual creo un código de buenas prácticas [12]. Desde 1994 la Organización Internacional de Normalización (ISO) ha participado en actividades enfocadas al ACV, lo cual dio como resultado la serie de normas ISO 14040/44 publicadas por primera vez en 1996 [10,13]. En las décadas de 1980 y 1990 el concepto de ciclo de vida aparece en el sector de la construcción [7,10,11]. A partir de estos años se han llevado a cabo numerosos estudios mediante ACV a lo largo del mundo, teniendo resultados cada vez más concluyentes y siendo posible su estandarización en el sector de la edificación y de la construcción en general.

Gracias a estos estudios ha sido posible establecer conclusiones relevantes sobre los impactos ambientales que se generan en la construcción y en la edificación. Por ejemplo, se sabe que considerar materiales y elementos eficientes en la construcción de los edificios reduce los impactos ambientales que éstos generan [14–16]; esto sin ser obligado el encarecimiento excesivo de los impactos ambientales incorporados [7,17] y siendo estas tasas de aumento remunerables a los pocos años de uso del edificio [18,19]. Además, se han encontrado ventajas evidentes en considerar el entorno urbano en los parámetros de diseño de las edificaciones [20–22].

De igual forma, ha sido posible establecer que en el ciclo de vida de los edificios un 80-90% de los impactos ambientales se suscita en su etapa operacional [23–31]; debido en su mayoría a la energía utilizada por la calefacción, ventilación y aire acondicionado [23,32,33]. Aunque gran parte de los estudios han establecido estas cifras, en otras investigaciones se ha encontrado que la proporción de la energía y de las emisiones incorporadas en el total del ciclo de vida dependen en gran manera de la zona geográfica y del clima [34,35]. Por ejemplo, la energía incorporada de una vivienda nueva con aislamiento adecuado puede representar el 40% del total del consumo de energía durante todo el ciclo [36] e incluso puede exceder a la energía operacional. O si se considera la tendencia de adoptar edificios de energía cero [37–39], lo esperado es que los impactos de las etapas incorporadas sean cada vez más cercanos a 100%, o lo que es igual, las etapas operacionales serán cercanas a 0% [40].

Por lo que, las etapas que consideran los impactos incorporados del ciclo de vida tienen y tendrán en un futuro próximo un papel imperante en el logro de la sostenibilidad de los edificios, ya que la elección de sus materiales y elementos será definitiva en el comportamiento del edificio a lo largo de su vida útil, tanto en su ahorro energético, como en las actividades de reparación, mantenimiento, reemplazo y remodelación. Además, estos impactos con respecto a su tiempo de ejecución generan altos índices de detrimento ambiental, por lo que su estudio es indispensable para lograr la tan buscada sostenibilidad en la construcción.

Para el desarrollo de esta tesis es importante realizar la definición y diferenciación de los impactos ambientales incorporados de un edificio (o de un producto de construcción) de los impactos de operación. Por lo que, es necesario definir un término ya establecido y estudiado con relativa amplitud en estudios previos, la energía incorporada (EE).

Se define a la EE de un edificio como la energía embargada en edificios y materiales de construcción durante todos los procesos de producción, construcción in situ, actividades del uso (mantenimiento, reparación, reemplazo, remodelación) demolición, gestión de residuos y eliminación final. Mientras que la energía operativa (EO) es la energía gastada en el mantenimiento del ambiente interior a través de procesos tales como calefacción y refrigeración, iluminación y operación de electrodomésticos [35]. Por lo que, los impactos ambientales incorporados serán todos aquellos que se deriven de las etapas definidas en la energía incorporada. Algunos de los impactos incorporados que fueron evaluados en esta tesis se definen a través de las siguientes categorías de impactos:

- Potencial de calentamiento global (PCG): es el responsable del cambio climático. Se genera por el incremento de los GEIs atribuibles a las actividades humanas que se originan por el forzamiento radiativo (absorción infrarroja en la región del espectro electromagnético entre 10 y 15 micrómetros). Está relacionado con la liberación de gases a la atmósfera, los más importantes son el CO_2, el metano (CH_4), el óxido nitroso (N_2O) y los compuestos orgánicos volátiles (COV) [41].
- Agotamiento de los recursos abióticos (ARA): se presenta en tres niveles de actividad (i) la reducción de las reservas hasta el punto de causar un agotamiento irreversible, como en el caso de los metales, los combustibles fósiles y otros minerales; (ii) recursos temporales o localmente agotables, tales como la turba (carbón ligero) y nutrientes del suelo; y (iii) recursos no agotables que tienen disponibilidad limitada, como la radiación solar y la lluvia [42].
- Potencial de acidificación (PA): se refiere a un exceso en la concentración de iones de hidrógeno (H+) en el sistema de agua y suelo (debido a procesos de lixiviación o bioquímicos). Las principales sustancias acidificantes son los óxidos de nitrógeno (NO_X), los sulfuros (SO_2) y el amoníaco (NH_3) [41].
- Potencial de eutrofización (PE): se refiere al enriquecimiento de nutrientes en las aguas superficiales (ríos, lagos y embalses). Las principales sustancias eutrofizantes son NO_X y NH_3 [43].
- Potencial de toxicidad humana (PTH): se refiere a los efectos de las sustancias tóxicas en el ambiente humano [44]. Los modelos de evaluación de impacto ambiental consideran sus factores de caracterización mediante la determinación de entre 180 y 1250 sustancias diferentes, pero que en general se pueden subdividir en sustancias orgánicas, inorgánicas y metálicas [45].

Estos impactos junto con la energía incorporada se eligieron por considerarse relevantes para el sector de la construcción, debido a la implicación que representan en la emergencia climática que se está viviendo en la actualidad.

1.2. EL ANÁLISIS DEL CICLO DE VIDA

Con el objetivo de abordar las tres dimensiones de la sostenibilidad (ambiental, económica y social) propuestas por Elkington en 1998 [46] se han integrado dos nuevas técnicas al ya conocido ACV (ambiental); éstas son el análisis de costo de ciclo de vida (ACCV) [47–49] y el análisis de ciclo de vida social (ACV-S) [50]. Estas tres metodologías conforman el análisis de sostenibilidad del ciclo de vida (ASCV). El ASCV se refiere a la evaluación de todos los impactos negativos ambientales, sociales y económicos en los procesos de toma de decisiones hacia productos más sostenibles a lo largo de su ciclo de vida [51]. Walter Klöpffer propuso la combinación de las tres técnicas y la puso en una fórmula conceptual [52].

ASCV = ACV (ambiental) + ACCV + ACV-S

Considerar un ASCV es primordial en la gestión del ciclo de vida (GCV), y por lo tanto en el pensamiento del ciclo de vida (PCV) [53,54]. Dado su carácter holístico, sistémico y riguroso, el ACV (ambiental) es la técnica preferida para compilar y evaluar información relacionada con los potenciales impactos ambientales de un producto [51]. Se define como la recopilación y evaluación de las entradas, salidas y posibles impactos ambientales de un sistema de productos a lo largo de su ciclo de vida [13]. Es una técnica aplicada por expertos en todo el mundo [51] que consta de cuatro pasos fundamentales, los cuales se esquematizan en la Figura 1.

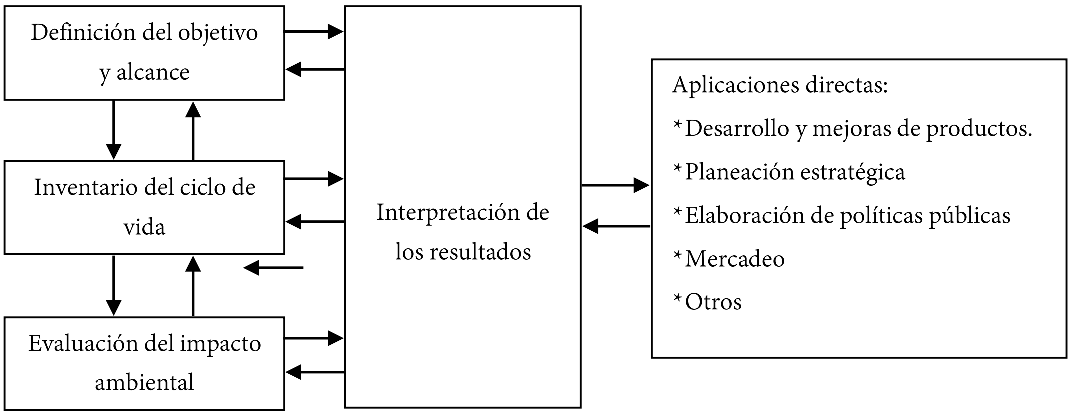

Figura 1. Esquema de las fases del ACV. Tomado de ISO 14040 [13].

En la definición del objetivo y el alcance se establecen los límites del sistema, la unidad funcional y la calidad del inventario del ciclo de vida. La profundidad y amplitud del ACV puede diferir dependiendo del objetivo particular; en el inventario del ciclo de vida (ICV) se recopilan los datos de entrada/salida en relación con el sistema bajo estudio; en la evaluación del impacto del ciclo de vida (EICV) los impactos ambientales de varios flujos de material y energía se asignan a diferentes categorías de impacto, el factor de caracterización se utiliza para calcular la contribución de cada uno de los componentes para diferentes categorías; y por último, en la interpretación de los resultados se resumen y discuten los resultados del ICV o de la EICV o de ambos como base para las conclusiones, recomendaciones y toma de decisiones de acuerdo con el objetivo y alcance definidos [7,8,13].

Las cuatro etapas del ACV se llevan a cabo en procesos iterativos, de tal forma que éste es un procedimiento flexible que permite regresar una y otra vez a las etapas previas y redefinirlas. Esta misma flexibilidad ha sido un motivo de diversidad entre los estudios que se han realizado, una característica que se puede considerar una ventaja, pero que también genera incertidumbre en la globalización de los resultados. Por este motivo, los procesos de normalización y estandarización se han ido actualizando basados en las discrepancias generadas en investigaciones realizadas.

1.3. NORMATIVA UTILIZADA Y LÍMITES DEL SISTEMA DE LOS IMPACTOS INCORPORADOS

Para poder garantizar transparencia y comparabilidad en los ACV, se requiere una definición clara de los límites del sistema temporal y físico. En la actualidad existen normas internacionales y europeas exclusivas para productos de construcción (ISO14025 [55] y EN 15804 [56]) y para estructuras de edificios (ISO 21931-1 [57] y EN 15978 [58]). Además, existe el anexo 57 de la IEA EBC, el cual establece los lineamientos para el estudio de los impactos de las etapas incorporadas en la construcción. El anexo 57 complementa a los estándares anteriores proporcionando mayor transparencia en el proceso del ACV (Figura 2) [5].

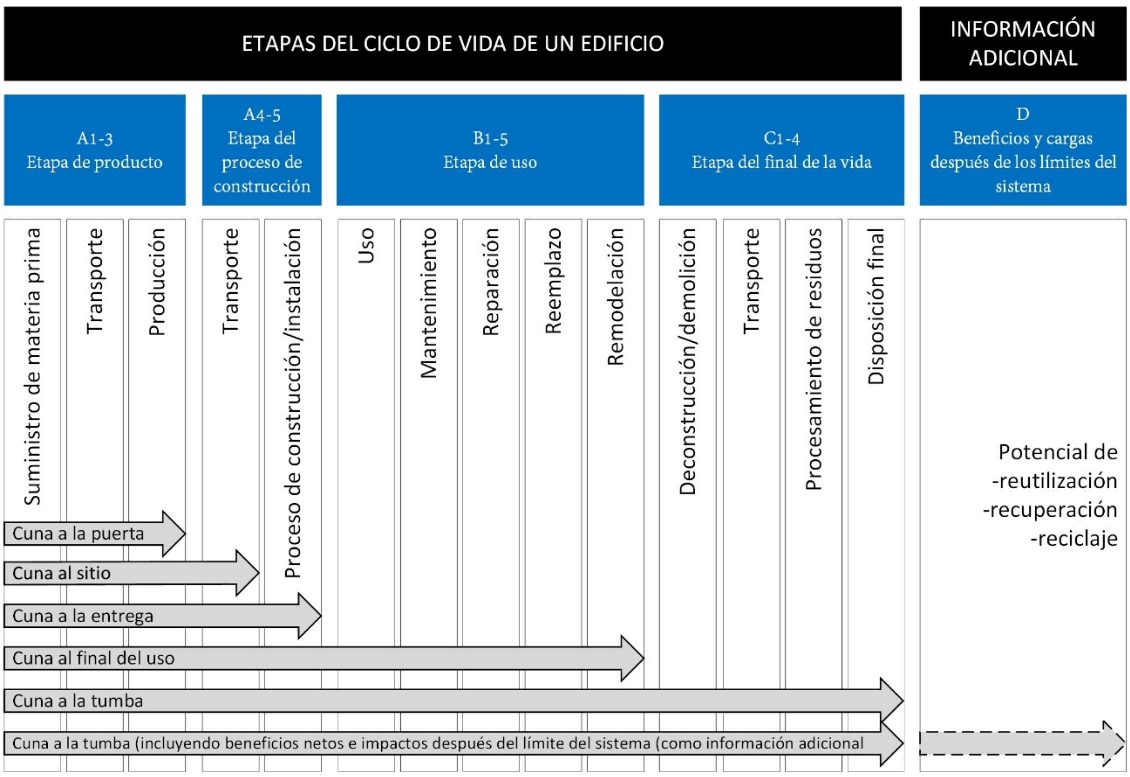

Figura 2. Modelo propuesto para la descripción y selección de los límites del sistema (estructura modular adaptada por EN 15978: 2011). Tomado de H. Birgisdottir et al. (2017) [5].

La figura 2 es una adaptación de la EN 15978 para el estudio de las etapas de los impactos incorporados de un edificio. Para llevar a cabo estos tres artículos se utilizaron los límites de sistema que se ilustran en esta figura, atendiendo de esta forma los lineamientos del anexo 57 y las normativas EN 15804 [56], ISO 21931-1 [57], EN 15978 [58] e ISO 14040/44 [13]. Algunos de los parámetros más relevantes de la aplicación de la metodología (abordadas con detalle en el capítulo siguiente) son la base de datos utilizada para el inventario de ciclo de vida, ecoinvent; dos de los artículos se apoyaron en los datos de cuantificación de materiales de BEDEC y otro más de CYPE Latam; y los métodos de impacto ambiental utilizados fueron CML 2001, Ecoindicador 99, IPCC 2013 y CED.

1.4. OBJETIVO DE LA TESIS

Esta tesis tiene como objetivo evaluar la aplicabilidad de la herramienta metodológica ACV en el sector de la construcción; en específico, en las denominadas etapas de los impactos ambientales incorporados del ciclo de vida en la edificación de vivienda y de su entorno urbano. Para llevar a cabo esta tesis se realizaron tres artículos, los cuales comparten la herramienta metodológica utilizada en su desarrollo, así como la normativa equivalente en su ejecución. Se plantearon tres problemas fundamentales en cada artículo.

1.5. OBJETIVO DE CADA ARTÍCULO

1.5.1. A Cradle to Handover Life Cycle Assessment of External Walls: Choice of Materials and Prognosis of Elements: proporcionar datos que faciliten la futura promulgación de regulaciones que permitan la elección de sistemas de muros adecuados y sostenibles. El estudio se realizó desde una perspectiva centrada en la construcción y; por lo tanto, analiza las etapas de producto y del proceso de construcción de veinte muros exteriores [56], es decir, es un estudio de la cuna a la entrega [5].

1.5.2. Life Cycle Assessment of residential streets from the perspective of favouring the human scale and reducing motorized traffic flow. From cradle to handover approach: evaluar los impactos ambientales con datos cuantitativos que se generan al priorizar a los habitantes de una ciudad durante el proceso de diseño de una calle. El estudio se realizó desde una perspectiva centrada en la construcción y; por lo tanto, analiza las etapas de producto y del proceso de construcción de dieciocho calles residenciales [56], es decir, es un estudio de la cuna a la entrega [5].

1.5.3. Environmental Challenges in the Residential Sector: Life Cycle Assessment of Mexican Social Housing: este trabajo tuvo dos objetivos (1) identificar el estado de los impactos ambientales más relevantes que ocurren en México enfatizando en el sector residencial y (2) lograr una aproximación de los impactos ambientales generados por este sector. Para lograr este último objetivo se analizó una vivienda social mexicana a lo largo de todo su ciclo de vida, es decir, es un estudio de la cuna a la tumba [5,57,58].

CAPÍTULO 2

BREVE DESCRIPCIÓN DE LOS ARTÍCULOS

2.1. PRIMER ARTÍCULO

En 2016, después de consultar el estado del arte hasta ese año, se encontró que era necesaria información referente a las etapas de los impactos ambientales incorporados. Estos impactos fueron considerándose en investigaciones previas, ya que algunos estudios demostraron que representaban una proporción significativa en el total de los impactos ambientales del ciclo de vida [35]. En septiembre de 2016 la Agencia Internacional de Energía abordó la importancia de evaluar la energía y las emisiones incorporadas, así como la necesidad de crear pautas para complementar la normativa existente, ya que este tipo de ACV variaba dependiendo las condiciones individuales de cada estudio [40].

Al momento de plantear el problema del primer artículo se detectó la necesidad de utilizar elementos de construcción que generen edificios eficientes en su operación, en específico en edificios plurifamiliares. Se encontró que la demanda energética de un edificio está vinculada a la eficiencia de su envolvente [59]. De ésta, las paredes externas son partes esenciales, ya que su diseño permite el control pasivo de las condiciones interiores del edificio [33].

Investigaciones previas sugieren que invertir recursos en las etapas de los impactos incorporados del edificio vuelve más eficiente su operación [17,60,61], como por ejemplo el uso de aislamiento para paredes externas [62–64]. Por lo que, en este estudio se buscó establecer qué muros tenían el mejor comportamiento ambiental incorporado, sin alterar (en la medida de lo posible) sus características básicas; es decir, buscando que su comportamiento operacional fuera similar. Por lo tanto, se estudiaron veinte configuraciones de muros exteriores que daban solución equivalente y cumplimiento de la normativa vigente del ámbito español, con posible aplicación al ámbito europeo.

Los muros exteriores evaluados tuvieron variaciones en sus espesores y en los tipos de materiales utilizados en cada capa. Las características que se consideraron en su diseño fueron referentes a las propiedades térmicas, las propiedades mecánicas básicas y la funcionalidad del muro (espesor). Se buscó la mínima variación en estas características hasta lograr las veinte tipologías.

Este estudio se realizó mediante un análisis de ciclo de vida "de la cuna a la entrega", es decir, se consideraron las etapas de producto (A1-A3) y del proceso de construcción (A4-A5); estudios previos realizaron análisis similares con el objetivo de proveer de herramientas para la obtención de información referente a la construcción y a mejorar las prácticas en ésta [6,65–72]. La unidad funcional que se utilizó para el fin planteado fue un m^2 de muro.

Se utilizaron dos bases de datos para la obtención de la información: BEDEC y ecoinvent. BEDEC es una base de datos de materiales de construcción que incorpora información de productos de edificación y urbanismo [73]. Ecoinvent es una base de datos de inventarios de ciclo de vida reconocida por ser transparente, actualizada y consistente [74]. A pesar de ser una base de datos suiza su aplicación es posible en el ámbito español por contener información de Europa. Se ha utilizado en numerosos artículos con resultados favorables [75–77].

Las categorías de impacto analizadas fueron cambio climático, agotamiento de los recursos abióticos, potencial de acidificación, eutrofización y toxicidad humana, oxidación fotoquímica, disminución de la capa de ozono, todas ellas incluidas en la línea base del método de impacto ambiental CML 2001 [44]. Este método expresa sus indicadores en kg de sustancia equivalente, lo que los hace expresables en términos técnicos y objetivos, y facilita su comparación con otras investigaciones; además, sus factores de normalización son de alcance europeo y global. Como apoyo para la obtención de estas categorías se utilizó la herramienta informática LCA Manager 1.3 [78].

2.2. SEGUNDO ARTÍCULO

Después de que se evaluó un elemento indispensable en la configuración de edificios sostenibles, los muros exteriores, y de que se corroborara la importancia de estudiar los impactos ambientales incorporados en la edificación de vivienda plurifamiliar, se buscó ampliar la investigación y considerar no solo al edificio, sino también a su entorno urbano. Se detectó un elemento tan básico como indispensable en su concepción: la calle.

La calle es uno de los elementos principales que definen la configuración del entorno urbano; éstas se encuentran en el corazón de las ciudades, dan forma a la salud humana y a la calidad ambiental, y sirven como fundamento en la economía. En muchas ciudades conforman más del 80% del entorno urbano [79]. Varios investigadores mostraron las ventajas que se pueden obtener en un entorno que priorice la escala humana durante el proceso de planificación urbana [80–83].

Similar al primer artículo se han encontrado estudios que realizan análisis con aspectos relacionados a las calles que favorecen los entornos peatonales; sin embargo, la mayoría se basan en la etapa de uso [84] descuidando los impactos ambientales asociados a las etapas incorporadas.

Por lo tanto, en este segundo artículo se realizó un estudio de la "cuna a la entrega" de dieciocho tipologías de calles residenciales, en las que se variaron tanto las dimensiones, como los materiales de sus elementos. Similar al trabajo anterior, se buscó que estas dieciocho alternativas tuvieran equivalencia en servicio y en sus propiedades elementales, como las propiedades mecánicas y sus dimensiones totales (ancho). Los materiales seleccionados para el diseño de las calles correspondían a los más típicos practicables en España y algunas partes de Europa. A partir de su diseño se llevó a cabo el análisis. Con estas opciones se buscó establecer la tasa de variación en los impactos ambientales al aumentar o disminuir la peatonalidad y el flujo no motorizado.

Para llevar a cabo el análisis se utilizó como unidad funcional un metro lineal de calle con un ancho constante de 13 m (1x13m). Al igual que en el artículo uno, las bases de datos utilizadas fueron BEDEC y Ecoinvent. Fue un estudio aplicado al ámbito español con posibilidad de aplicación al resto de Europa. Para llevar a cabo el análisis se utilizó la herramienta informática LCA Manager 1.3 [78].

Las categorías de impacto seleccionadas en esta ocasión fueron enfocadas a daños finales, por lo que se utilizó el ecoindicador 99 como método de impacto ambiental [44]. La premisa de este trabajo partió de un congreso enfocado a salud humana, el cual tenía participación multidisciplinar [85], algunas de estas disciplinas sin familiaridad con temas ambientales en el sector de construcción. Al ser el ecoindicador 99 un método de impacto ambiental más intuitivo que utiliza ecopuntos como unidades se consideró más apto para este estudio. Las categorías de impacto se agrupan en las siguientes áreas de protección (AoP):

- Calidad del ecosistema: acidificación-eutrofización, ecotoxicidad y ocupación de suelos.
- Salud humana: carcinógenos, cambio climático, radiación ionizante, agotamiento de la capa de ozono y efectos respiratorios.
- Recursos: combustibles fósiles y extracción de minerales.

2.3. TERCER ARTÍCULO

En el tercer artículo se retomó el estudio de la edificación, pero en esta ocasión se identificó una región territorial que requiere la exploración de su estudio desde diferentes perspectivas. Es decir, se evaluaron los impactos ambientales que se generan en un país de América Latina y el Caribe (ALC), México.

En México, más del 88% del parque de vivienda corresponde a vivienda social [86]. Se estima que en los próximos años se construirán 600,000 viviendas anuales [87]. En años recientes, se ha promovido el tema de la sostenibilidad en la construcción [88], por lo que, México se ha destacado entre los países de ingresos medianos-altos debido a su programa de finanzas para soluciones en vivienda. En este programa se abordan parámetros referentes a la operación de la vivienda, tanto a nivel edificio, como a nivel urbano [20]; sin embargo, no se consideran los impactos incorporados. Por lo tanto, se aplicó el ACV de las etapas de los impactos incorporados a una vivienda social mexicana. El caso específico que se evaluó se puede considerar como guía para países de ALC o países con características similares. Además, se abordó la problemática ambiental del sector residencial en este país y de forma general de ALC.

Las economías emergentes de ALC deben enfrentar importantes desafíos ambientales para poder evitar replicar el modelo de sociedad desechable de las naciones industrializadas [89]. De los países de ALC, México es el segundo más poblado [90]. En los últimos diez años ha tenido un crecimiento económico del 2.2% [91] y hasta 2017 un aumento anual de la población del 1.3% [92]; por lo tanto, se prevé un aumento en las necesidades energéticas en los próximos años, así como en las emisiones de GEI.

En 2015 México emitió 683 millones de toneladas (Gg) de CO_2 eq. El inventario contabilizó 148 Gg absorbidos por la vegetación, llevando el balance de emisiones netas a 535 Gg de CO_2 eq [93]. Es decir, generó el 1.4% del total de CO_2 y el 1.24% del total de CO_2 eq en el mundo (en el grupo ALC solo superado por Brasil) [94,95]. De estas emisiones, el sector de la vivienda es responsable del 3.1% de CO_2 eq (atribuidos a la energía de operación).

Además, en 2017 México ocupó el puesto 16 en la lista de países con el mayor consumo de energía. El consumo total de energía en este año fue de 5362.8 PJ, derivado de las actividades productivas del país, de las cuales el sector residencial es responsable del 14% debido a los requisitos operativos de la vivienda [96]. Existen otras emisiones y consumos de energía relacionados al sector residencial (y de la construcción, es decir, los incorporados), los cuales deberán ser obtenidos en estudios como el presente.

Por otra parte, México genera el 0.4% del total mundial de RCD y el 3.4% del RSU (segundo en la región de ALC). Aunque la suma de sus residuos es inferior a la de países como China, Estados Unidos e India, su impacto a escala nacional no debe ser ignorado ya que existen limitados protocolos de gestión y se carece de la infraestructura para su procesamiento [97–100].

El ACV se ha utilizado en México desde finales de 1990 [101]. Las temáticas en las que se han enfocado estos estudios son la gestión de residuos [101], la industria de la energía [102], de la minería [103], del clínker [104], la optimización de agua de lluvia [105,106], la energía de operación en la edificación [107], entre otros. De acuerdo con un estudio desarrollado por Valdivia, hasta 2014 se habían desarrollado 101 artículos que utilizaron la metodología [108]. Además del ACV se han utilizado herramientas que se apegan a los criterios del PCV, como las declaraciones ambientales de producto [88,109] o los sistemas de evaluación de la sostenibilidad [20].

Este artículo se llevó a cabo mediante un ACV de la cuna a la tumba de los impactos incorporados del ciclo de vida. La unidad funcional fue la vivienda. Los elementos que se incluyeron en el estudio son lo que según investigaciones previas más relevancia tienen en los impactos del edificio [26,27,49,110–113], la envolvente (vertical y horizontal), los muros interiores, las puertas, las ventanas y los acabados básicos. Se evaluaron un total de seis tipologías, a las cuales se les variaron los materiales utilizados en la configuración de las ventanas, los muros exteriores y los muros interiores. Se utilizaron dos bases de datos, CYPE latam y Ecoinvent 3.

Además, al estudiarse los retos ambientales que tiene el sector residencial en México y ante la emergencia climática mundial, se identificaron problemáticas cruciales como el cambio climático y el consumo energético. Por lo que, las categorías de impacto ambiental que se obtuvieron fueron el potencial de calentamiento global y la energía incorporada, ambas de carácter global, mediante los métodos de impacto IPCC 2013 y CED, respectivamente. Además, se obtuvieron dos categorías más que se encuentran en el CML 2001, PTH y ARA.

CAPÍTULO 3

ARTÍCULOS

ARTÍCULO 1:

A Cradle to Handover Life Cycle Assessment of External Walls: Choice of Materials and Prognosis of Elements

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A Cradle to Handover Life Cycle Assessment of External Walls: Choice of Materials and Prognosis of Elements

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Abstract: This research focuses on a comparison of 20 external wall systems that are conventionally used in Spanish residential buildings, from a perspective based on the product and construction process stages of the life cycle assessment. The primary objective is to provide data that allow knowing the environmental behavior of walls built with materials and practices conventionally. This type of analysis will enable promoting the creation of regulations that encourage the use of combinations of materials that generate the most environmentally suitable result, and in turn, contribute to the strengthening of the embodied stages study of buildings and their elements. The results indicate that the greatest impact arises in the product stage (90.9%), followed by the transport stage (8.9%) and the construction process stage (<1%). Strategies (such as the use of large-format pieces and the controlled increase in thickness of the thermal insulation) can contribute to reducing the environmental impact; on the contrary, practices such as the use of small-format pieces and laminated plasterboard can increase the environmental burden. The prediction of the environmental behavior (simulation equation) allows these possible impacts to be studied in a fast and simplified way.

Keywords: LCA; cradle to handover; external wall; construction materials; building components; envelope

1. Introduction

The construction industry is responsible for the unsustainable use of natural resources, and is an important source of air, soil, and water pollution [1]. Published data indicate that this sector uses between 30–40% of primary energy worldwide [2], with these figures including the energy required by the buildings [3–5]. The costs of the primary energy consumed by buildings for some countries are 23% in Spain, 39% in the United Kingdom, 47% in Switzerland, 50% in Botswana, 40% in Europe, 25% in Japan, 28% in China, and 42% in Brazil [6]. Most of this energy consumption is due to heating, ventilation, and air conditioning throughout the building's operating life [7–9]. Studies have shown that most of the environmental impacts occur in this phase, representing approximately 80-90% of the total impacts generated in the useful life of the building [8,10–17].

Currently, the energy demand of a building is closely linked to the efficiency of its envelope [6] as well as its thermal properties. The envelope includes the walls, ceilings, doors, windows, and any peripheral element of the building [18]. The thermal properties of the materials used will determine their ability to absorb or emit longwave solar radiation, particularly the U-value (thermal transmittance) [9].

Although there are relevant conclusions about the envelope's influence on the energy efficiency of a building, there is still no consensus about the implication of its construction and previous phases (A1–A3 product stage; A4–A5 construction process stage, UNE-EN 15804:2012 +A1 [19]) in the overall environmental impacts of the building. This may be because stages A1–A5 generate a lower environmental impact (between 8–20%) in the life cycle of the building [8,10–17]. It has been established in previous studies that the operation phase must be included in the life cycle assessment (LCA) as a priority [20], but without omitting the rest of the phases, since the impact cannot be considered negligible [7,21]. Some researchers [20,22,23] consider that investing resources in the embodied stages would lead to buildings becoming more efficient in the operational stage.

The external walls (EW) are essential parts of the building envelope, since they provide thermal and acoustic comfort; their design allows passive control of the interior conditions of the building through management of the external temperature transfer [9]. Previous studies have found that EWs are important contributors of embodied energy, due to the use of the large amounts of material that are required [24]. Some of the tested practices in the search for improved behavior include green walls for facades [25], the use of insulation for external walls [26–28], and the use of appropriately sized windows (glass with the correct thermal coefficients).

The correct choice of materials is capable of generating substantial environmental deflation throughout the complete life cycle of the building [29–31]. However, the use of these alternative technologies has been limited due to the incorrect assumption that buildings with high energy efficiency are also more costly to construct, and thus, from an economic perspective, are of less interest to developers [32,33].

The effects on the external wall due to environmental actions and the resulting impacts depend on several factors. These include the wall configuration, the combination of materials within the wall, the airtightness of the wall system, and the specifics of each building and location. This makes the LCA of walls and related research a necessity. The LCA is a recently adopted method in the construction industry; it is one of the dimensions of the life cycle sustainability assessment (LCSA) [34–36].

The LCA has allowed detailed studies of all stages in the life of a building (with reliable and comparable results). Despite being a relatively young methodology in this field, the LCA may provide a solution to the environmental challenges currently affecting the sector. These include the significant consumption of energy and raw materials, solid waste management, and greenhouse gas emissions (GHGs) [3,14,37–42], making this an essential instrument with a view to the future.

The studies in which the built-in stages of constructive elements are addressed in detail are limited because the greatest environmental implication arises in the operation of a building. On the other hand, there is also an important number of studies that analyze conventional and alternative construction materials. However, it is necessary to analyze how these materials behave when they are integrated in a constructive element of a building from a perspective specific to the design of the element (stages A1–A5), and not as a consequence of its use. In this sense, this research focuses on the study of that fundamental part of the envelope: the walls. The study was carried out from a construction-focused perspective, and thus analyzes stages A1–A5 of the LCA of a building [19]. The main objective is to provide data that facilitate the future promulgation of regulations that allow the election of adequate and sustainable wall systems.

2. Materials and Methods

2.1. Aim and Scope of the Study

The aim of the analysis was to compare the environmental performance of 20 external wall systems (of three layers) used in Spanish residential buildings through LCA, varying the materials used for each layer (type of wall and thermal insulation), and define the results of the environmental impact through a system of equations.

2.1.1. System, Boundaries, and Functional Unit

Each analyzed system has the function of an external wall that is part of an envelope of a residential building. The analysis proposed for this study is known as “cradle to handover” [43], which includes the stages: raw materials supply (A1), transport (A2), and manufacturing (A3) (product stage or cradle to gate); and transport from factory to site (A4) and construction process (A5) [19]. Figure 1 shows the flow chart of the life cycle inventory (LCI) process used in the studied external walls. The stages of use (B1–B7) and end of life (C1–C4) have not been considered in this research, as it is intended to define which walls are the most optimal (environmentally and thermally) from the perspective of their production and construction, rather than as a consequence of their use.

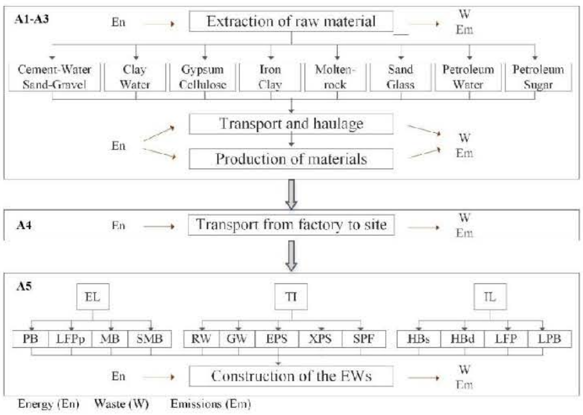


Figure 1. System boundaries of life cycle assessment (LCA).

In this sense, it has been taken for granted that the envelope of a building (especially the external walls) is decisive for having an important environmental impact in the operation stage; however, this hypothesis underestimates the impact of the envelope itself. In addition, considering the time in which each stage of the life cycle occurs, stages A1–A5 are developed in considerably shorter periods than stages B1–B7 (specifically B6 and B7). Therefore, the environmental implications of stages A1–A5 will be greater in terms of environmental impact/building lifespan.

Recent studies have carried out analyses of different types of constructions, such as buildings [44–48] or pavements [49–52], exclusively considering stages A1–A5 or similar (A1–A4 and A1–A3). The objective of these works is to help researchers conduct environmental assessments in a fast, effective and sustainable way [44], and provide tools that contribute to a better practice of the stages involved in the construction.

In this sense, researchers have studied the carbon footprint of conventional buildings [44] and the built-in energy of industrialized construction buildings that solve the growing demand for housing [46]. Meanwhile, to address the lack of energy data in construction, hybrid LCI models have been developed [47]. On the other hand, to promote the use of alternative materials, the environmental impacts caused by the use of wood and conventional materials in buildings have been compared [45,48].

For the purposes of the comparative study, a square meter of external wall was chosen as a functional unit; being a physical element, it is intuitive, easily understood, and easily compared. In previous studies [8,53,54], this criterion has ensured that the functional unit would lead to reliable results.

2.1.2. Data Inventory

Ecoinvent 3.2 was chosen as a database to obtain the LCI for the materials and processes used in this study. Ecoinvent is recognized internationally as being exhaustive and transparent, with up-to-date and consistent data for energy and material supply as well as for resource extraction, the use of chemical products, metallurgy, agriculture, waste management, and transport [55]. It has been widely utilized in previous building LCA studies [56–58]. Since Spanish-specific LCI data were not available [59], its application to the scope of research may be considered credible and reliable when considering information mostly referring to the European area.

To quantify the materials used in each component of the external walls, this study uses information from the data contained in the Structured Bank of Constructive Elements Data (BEDEC) of the Institute of Construction Technology of Catalonia (ITeC) [60]. BEDEC is a materials database with information on construction products, which incorporates constructive elements of typologies such as building, and contains technical characteristics referring to the Spanish area.

2.1.3. Impact Assessment Method and Categories

The CML 2001 (Leiden University's Center for Environmental Science) [61] was chosen as an environmental impact method, since it is considered for application in the Spanish sector and includes normalization factors of both European and global scope. Additionally, its indicators are given in kg of substance equivalent, which makes them expressible in technical and objective terms, and eases their comparison with other research. The CML includes impact categories of collective interest such as:

- Climate change (CC) [62]
- Depletion of abiotic resources (ADP) [63]
- Acidification potential (AP) [62]
- Eutrophication potential (EP) [64]
- Human toxicity (HTP) [65]
- Photochemical oxidation (POCP) [62]
- Stratospheric ozone depletion (ODP) [62,64].

The Software LCA Manager 1.3 [66] was used to support the management of information on the environmental impacts, which allowed the resources used and their environmental effects to be analyzed, ordered, grouped, and classified according to the LCA methodology [67]. This software has been used in previous studies, with satisfactory results [12].

2.1.4. Assumptions

For the evaluation of A4–A5, the following assumptions were made. For A4, the site of Plaza Cataluña was considered as the benchmark due to its central and strategic location. For A5, the number of floors aboveground (weighted average) of buildings destined for housing in Barcelona was established using the data obtained from its Department of Statistics [68]. A crane was considered for the construction process, which allows access to the material for the conformation of the walls. Therefore, buildings of one and two floors were discarded. Consequently, according to these criteria, the average building in Barcelona destined for housing is of six floors. In addition, it was considered that each of these levels has a between-floor height of three meters (2.5 m free between levels, with upper and lower slabs of $\approx$25 cm each) [69]. Therefore, the average height of reference (HR) used in A5 in this study is 18 m (including the complete up–down cycle).

3. Case Studies

For the present study, 20 external wall systems conventionally used in Spanish residential buildings were selected. Although the data provided for the proposed alternatives (materials and types of walls) correspond to the Spanish stock, these can be considered conventional, even in other European countries [25,38]. The external walls are composed of an exterior layer (EL), which is generally exposed to the thermal conditions produced by the climate; then, there is a thermal insulation (TI), which helps provide adequate hygrothermal comfort as well as energy efficiency; finally, there is an interior layer (IL) in contact with the habitable space of the system, which is subject to its own internal conditions.

The optimum comparative configuration of the external walls that were studied was carried out by means of an iterative process, which involved evaluating the different geometric thicknesses and the material types that make up each of the layers. With each proposed solution, the physical and mechanical properties of each external wall were then evaluated. Finally, those that showed equivalence in terms of a similar total thickness (EL + TI + IL), compression strength, and thermal and fire resistance (i.e. equivalent functionality), were chosen. The configuration and properties of the walls are shown in Figure 2.

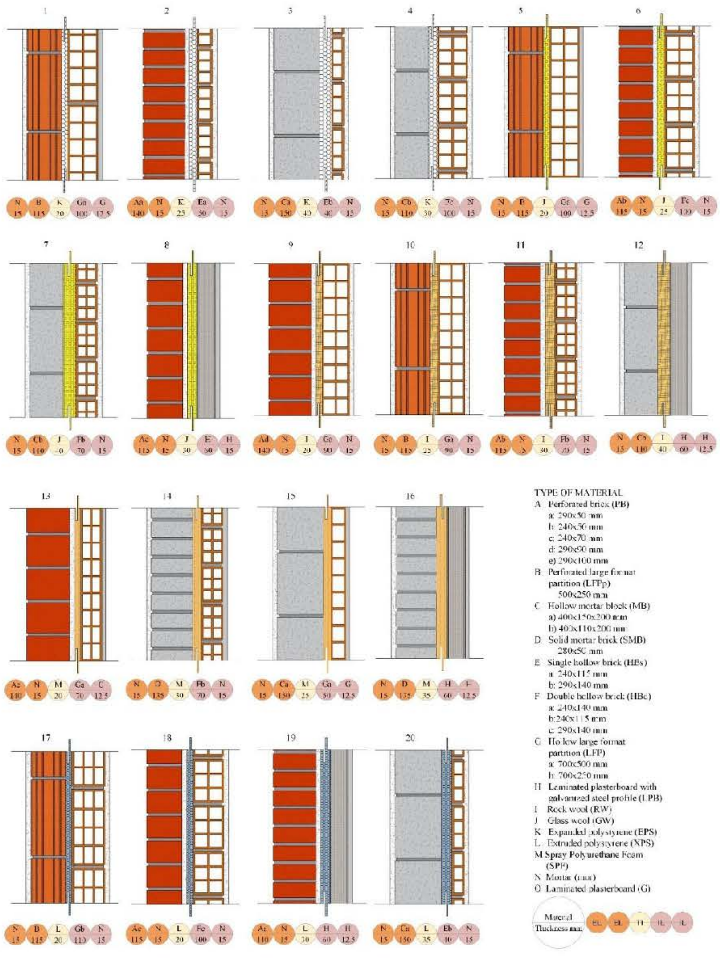


Figure 2. Configuration of the external walls.

With regard to the thermal requirements of the walls, they were dealt with in accordance with the basic document DB-HE-1 of the Spanish building technical code (CTE) [70] for the climatic zone classified as C2, corresponding to the city of Barcelona (Table B.1 of the DB-HE-1, climate zones of the Iberian Peninsula). The U-value in all of the external wall combinations studied was always below the established limits for facade walls and enclosures in contact with the terrain (0.73 W/m^{2}K).

Additionally, as a guarantee of equivalence among all of the systems studied, equivalent construction solutions were provided that showed a lower variation of U-value (0.098 W/m^{2}K) in all of the comparisons. The minimum U-value was 0.61 W/m^{2}K, and the maximum U-value was 0.70 W/m^{2}K. The average of the 20 systems was 0.65 W/m^{2}K. The thicknesses of each solution in their total transversal section were adjusted until a maximum variation of 16% was attained, with extreme dimensions of between 23.5–28 cm, these sections were considered conventional for external walls in multi-storey Spanish residential buildings. The U-value and thickness for each external wall are shown in Table 1.

Table 1. Properties of the external walls.

EW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
U-value (W/m^{2}K)	0.65	0.68	0.63	0.68	0.65	0.64	0.61	0.7	0.66	0.61	0.61	0.67	0.62	0.61	0.69	0.62	0.64	0.70	0.68	0.69
Thickness (cm)	26.3	24.5	26.0	27.0	26.3	27.0	25.0	23.5	28.0	26.0	24.5	23.8	25.8	26.5	25.3	25.8	27.5	26.5	25.8	25.5

The options chosen for making up the exterior layers were elements of ceramic clay pieces (CCP) and mortar pieces (MP) of grey cement. Ceramic clay pieces and laminated plasterboard (LPB) were used for the interior layers. Materials derived from natural wool and petroleum, with similar physical and mechanical performance, were chosen as thermal insulation. The specific physical characteristics of the elements chosen for configuring the walls are shown in Table 2. The finishes to cover the walls on their exterior and interior faces were of cement mortar (mor) and laminated plasterboard (G). The normalized compressive strength for the exterior and interior layers was 10 N/mm^2 and 3–5 N/mm^2 respectively, and was considered null for thermal insulation.

Table 2. Properties of materials used.

Element of Wall *	Type *	Material *	** λ (W/mK)	*** Fire Resistance	Density (kg/m^3)	Characteristics
EL	CCP	PB	0.35	A-1	780 **	High-density (HD) CCP with faced finish (FF) joined with industrial mor M7.5; category I UNE-EN 771-1 [71].
		LFPp	0.23	A-1	850 ***	HD CCP with coated finish (CF) joined with mor 1:2:10 of cement (CEM II); category I UNE-EN 771-1 [71].
	MP	MB	1.18	A-1	520–1230 **	MB pieces with CF joined with mixed mor 1:2:10; category I UNE-EN 771-3 [72].
		SMB	1.18	A-1	520–1230 **	SMB pieces with CF joined with mixed mor 1:2:10; category I UNE-EN 771-3 [72].
IL	CCP	HBs	0.32	A-1	770 **	Low-density (LD) partitions with CF joined with mixed mor 1:2:10; UNE-EN 771-1 [71].
		HBd	0.32	A-1	770 **	LD partitions with CF joined with mixed mor 1:2:10; UNE-EN 771-1 [71].
		LFP	0.29	A-1	650 **	LD partitions of 700 × 500 mm and variable thickness with CF joined with gypsum-based adhesive; UNE-EN 771-1 [71].
	LPB	LPB	0.25	A-2 S-1, d0	750–900 **	Self-supporting structure of galvanized steel profiles (GP), uprights each 400 mm (60 mm width), channels (60 mm width) with laminated plasterboard (G); UNE-EN 520 [73].
TI	Natural wool	RW	0.035	A-1	50 ****	Rigid plate positioned without adhering, UNE-EN 13162 [74].
		GW	0.036	A-1	40 ****	Semi-rigid plate positioned without adhering; UNE-EN 13162 [74].
	Petroleum	EPS	0.036	B-S1, d0	10–50 **	Smooth surface faces and smooth edge, without adhering; UNE-EN 13163 [75].
		XPS	0.036	B-S1, d0	25–50 **	Smooth surface faces and smooth edge, without adhering; UNE-EN 13164 [76].
		SPF	0.028	B-S1, d0	30–60 **	Spray polyurethane foam. Amorphous and projected; UNE-EN 14315-1 [77].
Finishes	mor		0.55	A-1	1000–1300 **	Mor CSIII W1 of 1.5 cm thickness. Mor CSIII W0 of 1.5 cm thickness; UNE-EN 998-1 [78].
	G		0.25	A-2 S-1, d0	750–900 **	Adhered with gypsum base over its entire surface [73].

* See Figure 2 for the definition of acronyms;** λ = Thermal conductivity. Spanish building technical code (CTE) [79]; *** Technical sheet of local material supplier; **** Structured Bank of Constructive Elements Data (BEDEC) [60].

The materials used have a limited or insignificant contribution to the spread of fire according to their classification in UNE-EN 13501-1. As these materials are of petrous origin, they are considered inert and incombustible, and are classified as A1 according to the Euroclasses for building elements [80]. The polymers (XPS, EPS, and SPF) are an exception, being combustible due to their organic nature, and have been classified as "category E" in the most unfavorable cases (direct exposure). However, for the final application of this work, they have been classified as B-S1, d0 because of the finish used (plaster and mortar) [81–83].

4. Life Cycle Inventory

4.1. Product Stage (A1–A3)

The inventory of the study was carried out after the samples had been defined, their equivalence of functionality corroborated (taking into account their most important physical characteristics), and the objectives and scope of the LCA established.

For the evaluation of the product stage (A1–A3), the quantities (by weight) of material required (WM_{FU}) to configure each element of the external wall were determined per the selected functional unit, the square meter. In each element studied, waste coefficients were applied. Only those components that exceeded 1% by the weight of each wall were considered. As the materials studied are either inert or the insulation of natural wools or petroleum derivatives, the percentage excluded does not represent a potential risk (substances neither dangerous nor highly contaminating). Table 3 shows the quantities for the boundaries established (A1–A3, A4, and A5) and the datasets selected from Ecoinvent.

Table 3. Life cycle inventory for 1 m^2 of each external wall (EW).

Stage	Element	Material/Process	External Walls 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ecoinvent Process/Material
A1–A3	EL	Ceramic clay pieces (kg)	91.6	130.6	-	-	91.6	109.4	-	114.5	117.5	91.6	109.4	-	119.9	-	-	-	91.6	114.5	130.6	-	Brick production, RER
		Mortar pieces (kg)	-	-	149.5	126.1	-	-	126.1	-	-	-	-	126.1		217.2	149.5	217.2	-	-	-	149.5	Concrete block production, RER
		Mortar (kg)	42.3	125.5	49.8	44.6	42.3	115.7	44.6	104.6	112.0	42.3	115.7	44.6	100.9	77.1	49.8	77.1	42.3	104.6	125.5	49.8	Cement mortar production, CH
	IL	Ceramic clay pieces (kg)	51.6	37.4	30.5	70.9	51.6	70.9	49.5	-	50.8	50.8	49.5	-	45.8	49.5	36.3	-	64.3	70.9	-	30.5	Light clay brick production, DE
		Mortar (kg)	-	43.3	41.3	52.8	-	52.8	58.6	-	37.0	37.0	58.6	-	-	58.6		-	40.2	52.8	-	41.3	Cement mortar production, CH
		Laminated plasterboard (kg)	9.5	-	-	-	9.5	-	-	13.3	-	-	-	9.5	9.5		9.5	9.5	-	-	9.5	-	Gypsum plasterboard production, RoW
		Gypsum (kg)	13.5	-	-	-	13.5	-	-	0.8	-	-	-	0.8	9.7		7.2	0.8	-	-	0.8	-	Stucco production, CH
		Steel (kg)	-	-	-	-	-	-	-	2.3	-	-	-	2.3	-	-	-	2.3	-	-	2.3	-	Steel production, converter, unalloyed, RER
		Zinc (m^2)	-	-	-	-	-	-	-	1.1	-	-	-	1.1	-	-	-	1.1	-	-	1.1	-	Zinc coating, coils, RER
	TI	RW (kg)	-	-	-	-	-	-	-	-	1.05	1.31	1.58	2.10	-	-	-	-	-	-	-	-	Rock wool production, CH
		GW (kg)	-	-	-	-	0.84	1.05	1.68	1.26	-	-	-	-	-	-	-	-	-	-	-	-	Glass wool mat production, CH
		EPS (kg)	0.63	0.79	1.26	0.95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Polystyrene foam slab production, RER
		XPS (kg)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.67	0.67	1.00	1.18	Polystyrene production, extruded, CO_2 blown
		SPF (kg)	-	-	-	-	-	-	-	-	-	-	-	-	0.72	1.08	0.90	1.26	-	-	-	-	Polyurethane production, rigid foam, RER
A4	EW	Lorry operation (tkm)	28.0	32.1	26.9	30.0	28.1	33.9	27.6	25.6	31.2	24.2	31.3	20.9	33.1	39.9	29.8	33.2	26.1	34.0	27.9	27.0	Transport, freight, lorry 16–32 metric ton, EURO4
A5	EW	Machine use (unit) (10E-7)	1.90	3.07	2.48	2.68	1.90	3.18	2.55	2.15	2.89	2.03	3.04	1.68	2.61	3.67	2.30	2.80	2.17	3.12	2.45	2.47	Building machine production
		Energy (kWh) (10E-1)	1.22	3.67	2.05	2.18	1.22	3.67	2.29	2.30	3.26	1.77	3.78	1.05	2.41	3.05	1.30	1.79	1.84	3.44	2.75	2.05	Market for electricity, low voltage, ES

4.2. Transport from Factory to Site (A4)

The evaluation of A4 considers the WM_{FU} (in tons) and the average distances from factory to site (in km). The distances were established by using the factory location of each material as the starting point and a central location in the city of Barcelona as an end point, for which a map application with geo-referencing and a route optimizer (Google maps) was used. For each type of material, the average of three factories, located in a radius of approximately 100 km, is considered. The average distances (AD) used were as follows: 70 km for CCP; 60 km for MP, 25 km for mor; 125 km for LPB; 100 for RW, GW, and XPS; 50 km for EPS; and 60 km for SPF.

A lorry with the following characteristics was considered for transporting the external walls components: load capacity (LC_L) of 16 tons, cabin dimensions of 2.1 m wide by 2.2 m high, and a distance between axles of 3.5 m. These specifications satisfied the requirements of weight and maximum size for short-haul transport within a city [84]. Equation (1) was used for the environmental evaluation related to the movement impacts of the lorry (MI_L in ton-kilogram, tkm):

$$MI_L = AD \times WM_{FU} \tag{1}$$

4.3. Construction Process (A5)

Stage A5 contemplates the use of machines to transport the material to each floor of the building and the elaboration of the binders used in the manufacturing of the walls. First, Equation (2) was used to estimate the time of use required (TU_C [h]) for a two-ton crane (load capacity (LC_C) with an average velocity (VA_C) of 16.5 m/min, a potency (P_C) of 7.5 kW, and a useful life (UL_C) of 10,000 h [55]) to complete a full cycle to the center of the building (HR is 18 m). Similarly, two more parameters were determined by means of Equations (3) and (4) for evaluating the crane's impact: the portion of use (crane: PU_C [h/h]) and the operating energy required (EO_C [kWh]):

$$TU_C = \frac{\left(\frac{WM_{FU}}{LC_C}\right) \times H_R}{V_C} \tag{2}$$

$$PU_C = \frac{TU_C}{UL_C} \tag{3}$$

$$EO_C = TU_C \times P_C \tag{4}$$

Finally, with regard to the manufacture of the mortar mixes used in joining the ceramic pieces and the finishes, as well as for the plaster mixes used in the adhesion of the laminated plasterboard of each wall separately, the operating energy (EO_M [kWh]) of a continuous mixer was considered (average flow capacity (FC) of 13 l/min and a nominal potency (P_M) of 2.2 kW). The volumes of binder (V_B = sum of plaster and mortar in each wall) were quantified and, considering the FC, the time of use required (TU_M) was obtained. The EO_M required for the job was obtained by using the P_M. By means of Equations (5) and (6):

$$TU_M = \frac{V_B}{FC} \tag{5}$$

$$EO_M = TU_M \times P_M \tag{6}$$

5. Results of the Environmental Impact

5.1. Stages of Product (A1–A3) and of the Construction Process (A4–A5) in the Impact Categories

The environmental impact assessment establishes a link between the elementary inputs to the system of the products and processes analyzed, and their potential environmental impacts [85]. Figure 3 shows the percentage of environmental damage generated by the average of the 20 external walls (including all of their elements) in each stage analyzed. For all of the categories, the greatest environmental impact arises in the product stage (A1–A3), with an average of 90.9%, confirmed by previous research [12,47]. The subsequent stage is the transport from the factory to the construction site (A4), with 8.9% of the average impact. Lastly, the construction process stage (A5) generates less than 1% of the environmental load. The values obtained for transport and construction, despite depending on the inventory data of this study and the regional characteristics established, are consistent with the results of other investigations [30,38,49].

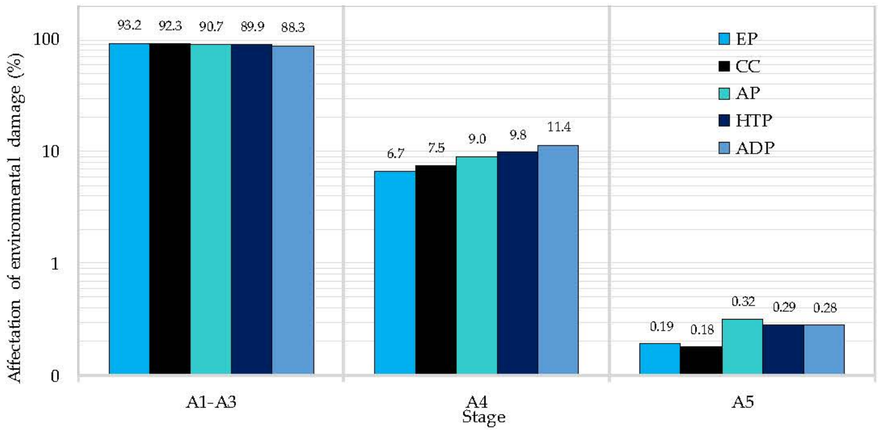


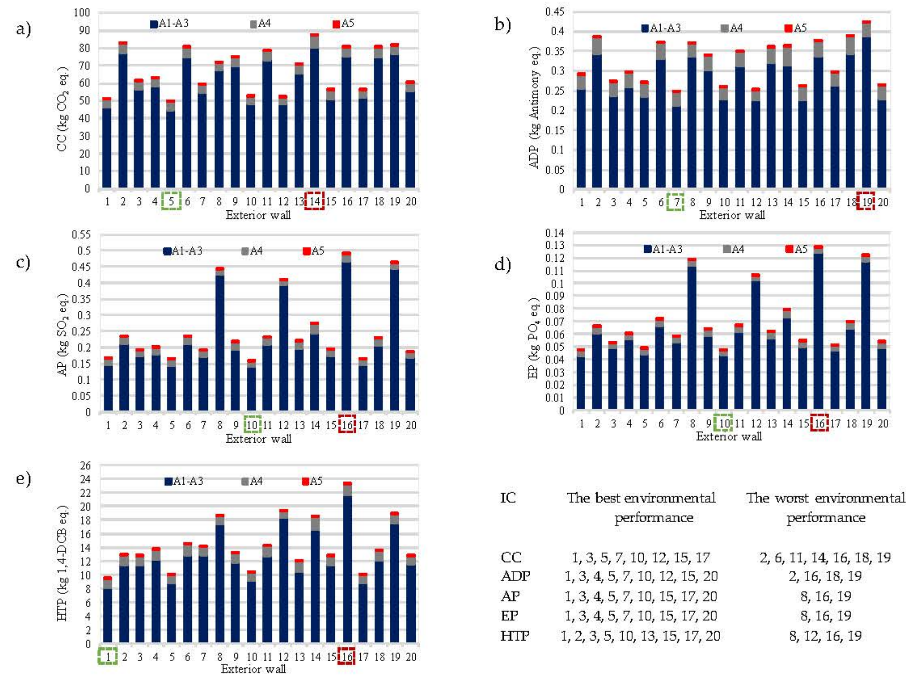
Figure 3. Percentages of the environmental damage of the average of the external walls in stages A1–A5 for all of the impact categories.

The impact categories with the greatest repercussion in the product stage (A1–A3) are EP (93.2%) and CC (92.3%). This is because most of the GHGs (mainly CO_2 and N_2O) are part of the chemical reactions that occur during the manufacturing of conventional products that are used in the construction of walls, such as mortar and clay pieces. The high temperatures used in the firing of the ceramic pieces, over 1300 °C [86], and the cement clinker, over 1400 °C, as well as the high content of carbonates found in their most important raw materials (limestone and clay) are responsible for the release of CO_2 into the atmosphere [87]. Similarly, the production of nitrogenous gases is inevitable due to the high temperatures reached in cooking the pieces [88]. In the stages of the construction process, the ADP presents the highest values for A4, with 11.4%, and the AP for A5, with 0.32%. This is because the transport sector is closely linked with the use of fossil fuels (sources of potentially acidifying substances, such as NO_X and SO_2 emissions) [89].

With regard to the POCP and the ODP, the 20 walls only reached values of the order of 10E-3 (kg ethylene eq.) and 10E-6 (kg CFC-11 eq.), respectively, at their most polluting stage (A1–A3). The first of the categories is due to the problem of air quality, which is caused by a combination of high-density car traffic in urban areas, strong incidences of solar radiation, and the high frequency of meteorological situations that inhibit air circulation (factors that impact on the formation of ozone and toxic gases in the troposphere) [62]. On the other hand, with respect to ODP, the agreements established in the Montreal Protocol limit the substances in this category to critical or essential uses [64]. The contribution to both impact categories generated by the use of external walls was considered as null, because the activities that produce them are not present in the analyzed stages.

5.2. The External Walls in the Environmental Impact Categories

The external walls with the best overall environmental performance were walls 1, 3, 5, 7, 10, 15, 17, and 20, which presented the most favorable values in a minimum of four impact categories (and of these, the walls 1, 3, 5, 10, 15, and 20 in the five categories). Figure 4 shows the results of the five impact categories for the 20 external wall systems, including the three elements that compose them and the stages analyzed. As a selection criterion, the wall with the best environmental performance was taken as a reference. Consequently, only those that were 10% above this value were selected, assuming that these walls could be considered equivalent to the reference wall for each category. Walls 7 and 17 did not meet this criterion in some of the five impact categories (seven in HTP, 17 in ADP), but they are still considered acceptable, as their values continue to be close to this one.



IC	The best environmental performance	The worst environmental performance
CC	1, 3, 5, 7, 10, 12, 15, 17	2, 6, 11, 14, 16, 18, 19
ADP	1, 3, 4, 5, 7, 10, 12, 15, 20	2, 16, 18, 19
AP	1, 3, 4, 5, 7, 10, 15, 17, 20	8, 16, 19
EP	1, 3, 4, 5, 7, 10, 15, 17, 20	8, 16, 19
HTP	1, 2, 3, 5, 10, 13, 15, 17, 20	8, 12, 16, 19

Figure 4. Total value of each indicator (**a**) climate change (CC), (**b**) depletion of abiotic resources (ADP), (**c**) acidification potential (AP), (**d**) eutrophication potential (EP), (**e**) human toxicity (HTP) in stages A1–A5 for each EW (EL + TI + IL).

The walls with the best overall environmental performance (1, 3, 5, 7, 10, 15, 17, and 20) have the use of large-format lightweight pieces in their conformation (such as LFPp or MB) in common, and in some cases, the option of tongue and groove. The manufacture of lighter walls (mortar and clay) will require less raw material, and therefore lead to a reduction in substance generation. In addition to the optimization of the binders destined for their conformation, reductions could be made in the impacts produced in the construction process (lighter walls generate up to 60% less pollution for CC, AP, and EP, 70% for ADP, and 30% for HTP).

For the selection of the walls with the worst environmental performance, the wall with the most unfavorable value was considered as the reference for each impact category, along with all those lower than it by 10% (see Figure 4). The options 2, 16, 18, and 19 are the ones with the worst environmental profile in the CC and in the ADP; they have the use of compact and small-format pieces for the conformation of the walls in common. With respect to the AP, EP, and HTP, walls 8, 16, and 19 presented the most adverse values; in addition to having dense and small-format pieces in the exterior layer, they use LPB as the interior layer. Therefore, the impact is attributed to both the heavy walls and the use of the galvanized profile of the LPB. The most unfavorable combination for all of the categories are walls 16 and 19, with an exterior small-format layer and an interior layer of LPB.

Considering not only the environmental profile, but also their U-value, the walls that could be recommended as suitable systems are numbers 7 and 10 (U = 0.61 W/m^{2}K [Umin]), wall 3 (U = 0.63 W/m^{2}K), wall 17 (U = 0.64 W/m^{2}K), and walls 1 and 5 (U = 0.65 W/m^{2}K), all of which were below the average U (0.65 W/m^{2}K). The walls with the worst thermal and environmental performance are 19 (U = 0.68 W/m^{2}K) and 8 (U = 0.7 W/m^{2}K). This suggests that the selection of elements with better physical capacities can in turn generate a lower environmental burden; therefore, this selection of elements and materials will be a determining factor in environmental optimization. In addition, the use of external walls with better thermal capacities could lead to savings in the operation stage of the building (B6); consequently, the environmental load will continue to be smaller.

When analyzing the five impact categories, two main groups emerged in terms of the trends shown in the results obtained. On the one hand, CC and the ADP are proportionally related, since the causes of GHGs mostly originate in the use of abiotic resources. In the case of AP, EP, and HTP, the first two, despite being different phenomena, are generated by the same substances (even the Eco-indicator 99 includes them in the same impact category).

5.3. The Constructive Elements (EL, TI, and IL) in the Product Stages (A1–A3)

The impacts of the different construction components (EL, TI, and IL) that make up each external wall of the study in stages A1–A3 (due to the significance of their maximum environmental impact) are presented in Figure 5. In this study, for the CC and the ADP, the amount of material (in weight) defines the general behavior of the external walls (and secondly the type of material). Therefore, the exterior layer generates the most environmental impact on these categories, followed by the interior layer and the thermal insulation. In the case of impact categories HTP, AP, and EP, behavior is influenced more by the type of material than the quantity. On the horizontal axis of Figure 5, the type of material that composes each element of the wall (see the nomenclature in Figure 2) can be seen, followed by the external wall containing it (for example, Aa: perforated brick of 290 mm x 50 mm, incorporated in walls 12 and 19). Figure 5d includes the AP and the EP, because the results for these categories show the same trend (with different values).

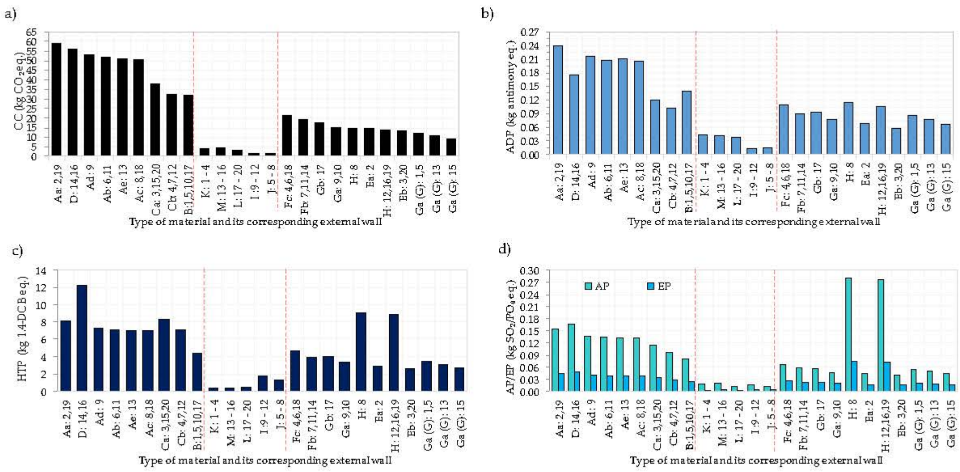


Figure 5. Detail of the elements of the EWs (and materials) in stages A1–A3 for the (**a**) CC, (**b**) ADP, (**c**) HTP, and (**d**) AP and EP.

The results for the exterior layers are shown in the first segment of Figure 5a (CC) and Figure 5b (ADP). The walls made with ceramic clay pieces generate 1.14 times more CC and 1.5 times more ADP than those made with mortar pieces. This is despite cement, which is known for its high pollutant rates [90], being a fundamental component in the manufacture of mortar. However, the mortar pieces only contain about 15% cement [55], and since the rest of its components are aggregates and water, the ceramic options are more harmful for these impact categories. Previous research has found that clay piece walls are more significant in terms of environmental impact than mortar piece walls [91]. In addition, the exterior layers made with small-format pieces (PB: 12, 19, 9, 6, 11, 13, 8, 18; SMB: 14, 16) are up to 60%, and 70% more polluting than those of large-format (LFPp: 1, 5, 10, 17; MB: 3, 15, 20, 4, 7, 12) for CC and ADP, respectively.

In the second segment of Figure 5a,b, it can be seen that thermal insulations made from hydrocarbons (XPS, EPS, and SPF) are on average 2.3 (CC) and three (ADP) times more harmful than natural wool (GW, RW). Therefore, from this perspective, it would be preferable when building external walls to use a thermal insulation such as GW and RW.

The third segment of the same figures shows that the interior layers made with ceramic clay pieces generate 1.14 times more CC than those made with LPB, although they represent only 15% by weight of the ceramic pieces. The interior layers of LPB (8, 12, 16, and 19) generate 1.27 times more ADP than the rest of the interior layers. In addition, the influence of G as finished (ILs 1, 5, 13, and 15) can be observed.

In the first segment of Figure 5c,d, the results of the exterior layers are shown regarding HTP and AP–EP. The exterior layers that use mortar pieces generate 1.4 times more HTP than those using ceramic clay pieces. This may be due to the heavy metals and volatile elements present in cement production [88], or the use of alternative fuels that incorporate hazardous waste [92] (such as potential generators of polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofuranes (PCDF) [93]). Previous research has found similar results for HTP and AP [94]. The exterior layers made with ceramic clay and mortar pieces have a similar behavior for AP and EP. This can be attributed to the sulfurous processes that take place in the production of both types of industries for ceramic and mortar pieces (due to the fuels used and the raw material) [86]. For the three previous categories, the options made up of small-format pieces are up to 51% more polluting than those of large-format pieces (MB and LFPp).

In the case of thermal insulations (the second segment of Figure 5c,d), the natural wools generate 3.4 times more HTP than those derived from petroleum. For the case of the AP, petroleum-based thermal insulations are 1.15 times more polluting than those derived from natural wool. The contribution that thermal insulations have in the EP was considered null for the quantities that are needed in the configuration of these external walls.

The results for the interior layers are shown in the third segment; those made with LPB presented 2.5, 5.3, and 3.7 times more HTP, AP, and EP, respectively, than those made with ceramic clay pieces. These values are 80% (minimum value for the three impact categories) due to the galvanized film that covers the steel profile (also found in previous studies [12]); so, the laminated plasterboard (G) itself does not represent a substantial problem in the generation of these categories. The interior layers of large-format pieces (LFP) are on average 21% less polluting than those of hollow bricks (HB) for the three impact categories.

6. Prediction of the Environmental Behavior of E Components

To establish the predictive behavior of the environmental effect that may be generated by the different possible combinations of the components studied here, a statistical analysis of the information obtained from the LCA was carried out, and the regression equations were determined by means of numerical analysis.

The relationships between the quantity of material used in making the external walls and the generation of indicators for each impact category studied are shown in Figures 6 and 7; from these, the impact increase rates (IIR, by establishing linear regression equations) were obtained for each type of material used in each component of the external walls. The general behavior of all of the studied variables is of a linear increase in the equivalent substance of each indicator with the increase of the mass quantity of the material to be used (linear relationship).

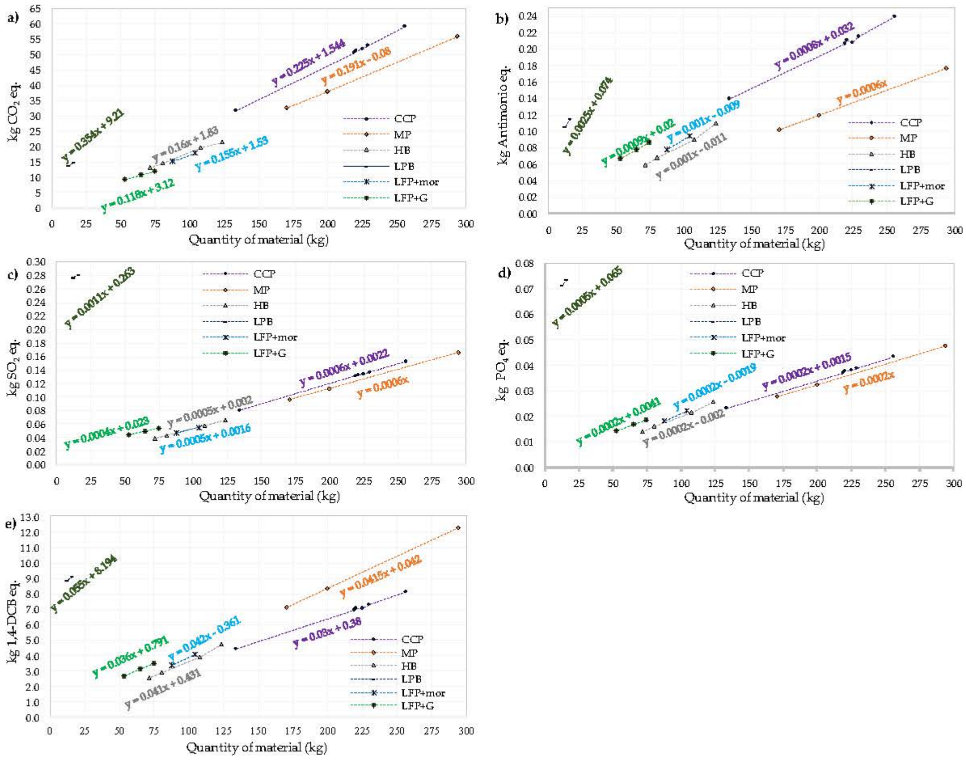


Figure 6. Linear regression for EL and IL in: (**a**) CC, (**b**) APD, (**c**) AP, (**d**) EP, and (**e**) HTP.

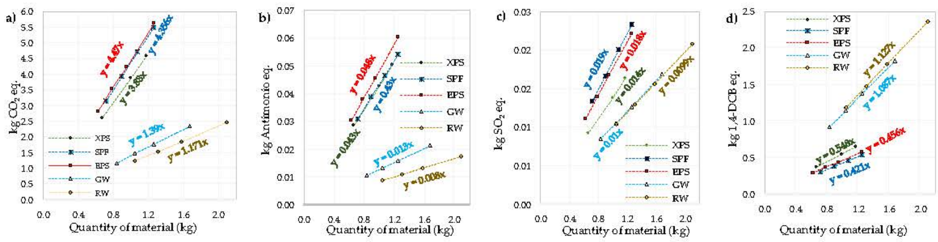


Figure 7. Linear regression for TI in: (**a**) CC, (**b**) APD, (**c**) AP, and (**d**) HTP.

Once the linear regression models of each indicator have been established, the general equation integrative (GEI, Equation (7)) can be proposed. This permits the estimation of the integrated behavior of the different external walls that use the conventional spectrum of the proposed building materials. In this equation, the independent variables are the quantity of materials (in kg) that are used to make up the exterior layers (a), interior layers (b), and thermal insulations (c). The dependent variable is the quantity of CO_2 eq. (Figures 6a and 7a), kg of antimony eq. (Figures 6b and 7b), kg of SO_2 eq. (Figures 6c and 7c), kg of PO_4 (Figure 6d) or kg of 1.4-DCB eq. (Figures 6e and 7d), which is generated by each component of the external wall. Table 4 includes the coefficients of the linear regressions that provide a solution for the GEI and the R^2 coefficients obtained in order to make a prediction of the environmental impact of the five impact categories analyzed.

$$\mathrm{GEI} = \mathrm{ax} + \mathrm{by} + \mathrm{cz} + \mathrm{d} \tag{7}$$

where: a, b, and c are obtained from Table 4; d is determined with the equation:

$$\mathrm{d} = \mathrm{d}_1 + \mathrm{d}_2 + \mathrm{d}_3 \tag{8}$$

where: d_1, d_2, and d_3 are obtained from Table 4.

The GEI allows an environmental profile to be obtained simply and practically of any element to be used, either in the design or recovery (or maintenance) of a building, by selecting one or more of the materials included in this study.

Table 4. Regression coefficients for the prediction of the general equation integrative (GEI) of the EWs.

	CC			ADP			HTP			AP			EP		
	a	d_1	R^2	a	d_1	R^2	a	d_1	R^2	a	d_1	R^2	a	d_1	R^2
CCP	0.225	1.544	0.99	0.0008	0.0320	0.99	0.030	0.380	0.99	0.0006	0.0022	0.99	0.0002	0.0015	0.99
MP	0.191	−0.080	0.99	0.0006	0.0000	0.99	0.042	0.042	0.99	0.0006	0.0000	0.99	0.0002	0.0000	1.00
	b	d_2	R^2	b	d_2	R^2	b	d_2	R^2	b	d_2	R^2	b	d_2	R^2
HB	0.160	1.830	0.99	0.001	−0.011	0.98	0.041	0.431	0.97	0.0005	0.0020	0.99	0.0002	−0.0020	0.96
LPB	0.354	9.210	1.00	0.003	0.074	1.00	0.055	8.194	1.00	0.0011	0.2630	1.00	0.0005	0.0650	1.00
LFP+mor	0.155	1.530	1.00	0.001	−0.009	1.00	0.042	−0.361	1.00	0.0005	0.0016	1.00	0.0002	−0.0019	1.00
LFPp+G	0.118	3.120	0.99	0.001	0.020	0.99	0.036	0.791	0.99	0.0004	0.0230	0.99	0.0002	0.0041	0.99
	c	d_3	R^2	c	d_3	R^2	c	d_3	R^2	c	d_3	R^2	c	d_3	R^2
XPS	3.880	0.000	1.00	0.043	0.000	1.00	0.548	0.000	1.00	0.0140	0.0000	1.00	_	_	_
SPF	4.356	0.000	1.00	0.043	0.000	1.00	0.421	0.000	1.00	0.0190	0.0000	1.00	_	_	_
EPS	4.470	0.000	0.99	0.048	0.000	0.99	0.456	0.000	0.99	0.0180	0.0000	0.99	_	_	_
GW	1.390	0.000	1.00	0.013	0.000	1.00	1.087	0.000	1.00	0.0100	0.0000	1.00	_	_	_
RW	1.171	0.000	1.00	0.008	0.000	1.00	1.127	0.000	1.00	0.0099	0.0000	1.00	_	_	_

7. Sensitivity and Uncertainty Analysis

In LCA studies, merging sensitivity and uncertainty analysis are used to assess the robustness of the results and their sensitivity to data, assumptions, and models [95]. The relevance of this analyses has been pointed out by several researchers [50,95–101], which contribute to focused research efforts and also provide support in the interpretation of LCA study results [102], particularly in studies when the input data of the LCI has not been documented or are unreliable [100,103].

In this study, the information related to the input data comes from assured sources, which are widely used in the daily practice of the construction industry. Also, the processes considered correspond to what is stipulated by the Europe normative, which substantially reduces the uncertainty because the information is sufficiently available, in addition to the use of the Ecoinvent database already recognizing uncertainty in their probability distributions [95,100,102,103]. Due to the above, and because the present study considers the cradle to handover approach, the stage that could present a higher degree of uncertainty in data collection is the transport from the manufacturing plants to the construction site (A4).

With the aim of determining the environmental and human health effects caused by the extension of uncertainty propagation produced by the A4 stage, this study considers several combinations between the locations of the manufacturing plants and different ecological performances of the machines used for the transportation of materials at the construction sites (Table 5). Previous studies [50] have presented similar approaches in conducting sensitivity analyses.

For the location of the manufacturing plants, the distances used in this work that are taken as a reference are called "lorry"; from these, three alternatives are analyzed: lorry ±50% of the distances, and 200 km. On the other hand, the behavior of Euro 5 and Euro 6 engines [104] are compared with Euro 4, which generates a total of 11 more scenarios than the base scenarios (scenarios B).

Table 5. Scenarios according to the established parameters.

Motorization	Lorry (−50%)	Lorry (Original)	Lorry (+50%)	Lorry (200 km)
Euro 4	Scenarios A	Scenarios B *	Scenarios C	Scenarios D
Euro 5	Scenarios E	Scenarios F	Scenarios G	Scenarios H
Euro 6	Scenarios I	Scenarios J	Scenarios K	Scenarios L

* Base scenarios.

According to sensitivity analysis, results vary in relation to the function of the indicator. The same occurs with the uncertainty percent that is presented in each of the cases according to the different scenarios considered, in which: (i) CC shows values between 7.37% (case 8) and 10.65% (case 7); (ii) ADP shows values from 10.25% (case 8) to 17.70% (case 7); (iii) AP shows values from 3.64% (case 12) to 11.94% (case 6); (iv) EP shows values from 2.96% (case 12) to 8.75% (case 2); and finally, (v) HTP shows values from 5.69% (case 12) to 15.37% (case 2).

The analysis highlights the relevance of the consideration of the A4 stage in the LCA, because the results obtained by the external walls in the different scenarios (Figure 8) show significant variations, which can mean increases of up to 42.18% and reductions of up to 8.06% in the environmental impacts produced during stages involved in the cradle to handover approach (A1–A5). The ADP and AP categories are those that present the most significant changes.

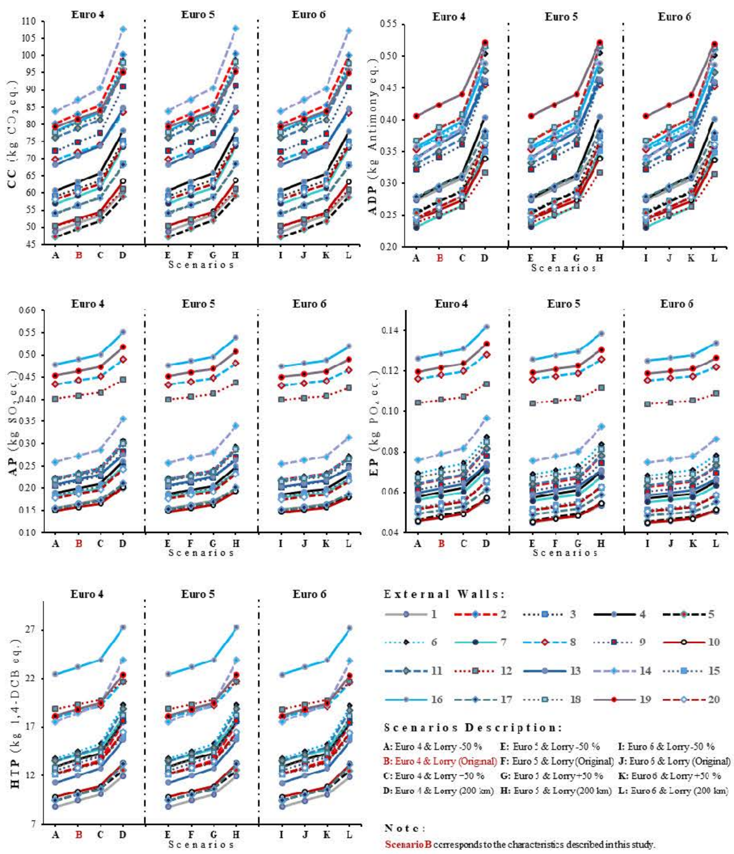


Figure 8. Results from the sensitivity analysis.

In terms of the ADP category, in which the largest increases occurred, the changes produced in scenario H in relation to scenario B show different variations in the interpretation of the original results; e.g., external wall 7 (which presented the best environmental performance in scenario B), would be 10.15% more polluting than external wall 12 (which presented the best environmental performance in scenario H). Also, consider external wall 8, which went from producing 14.11% less environmental impact than the case with the worst environmental performance in scenario B to producing only 1.57% less environmental impact than the case with the worst environmental performance in scenario H. In the case of both scenarios, the external wall with the worst environmental performance is external wall 19. On the other hand, in scenario H, the external wall 3 would not be considered between the external walls with the best environmental performance, because the impacts produced would be higher than 15% of those produced by the external wall 12.

Regarding the AP, the category in which the most significant reductions occurred, the position of each external wall in relation to the others was not affected. However, in this category, together with EP, the change from the Euro 4 engine to the Euro 6 engine exhibited more significant reductions in the environmental performance of the external walls.

Figure 8 also shows that variations in the locations of the manufacturing plants have a more significant impact than changes in the motorization of the machines used for transportation, except for the AP and EP categories, in which, the change from the Euro 4 engine to the Euro 6 engine generates reductions between 0.19–1.33% despite increasing the distances in the locations of the manufacturing plants by 50%. EP is the category with the most significant reductions; nevertheless, when the external walls consider scenario H, the increments varied between 2.90–9.80% in the EP, and 4.31–15.81% in the AP. Future studies could analyze the distance in which the change from the Euro 4 engine to the Euro 6 engine stops producing reductions in the environmental behavior of the external walls.

Among the results obtained by sensitivity analysis, it underlines that there is an increase in environmental performance only in the CC and ADP categories when changing from the Euro 4 engine to the Euro 5 engine. This increase varies between 0.04–0.13%; CC is the category in which the most substantial increases occur. Notwithstanding the above, general results support that renewing the vehicle fleet is an effective strategy to reduce its pollution effects [50,105,106], because all of the cases present reductions when the change is from the Euro 4 engine to the Euro 6 engine.

8. Conclusions

This study has made a comparison of the life cycle in stages A1–A5 of external walls conventionally used in Spanish residential buildings. The use of LCA established significant derivations among the considered perspectives, showing itself to be an efficient instrument for promoting sustainability in the construction industry.

The stages with the greatest environmental impact in all of the categories were A1–A3, which were more aggravating in EP (93.2%) and CC (92.3%). In stages A4–A5, the ADP and AP presented the highest values (11.4% and 0.32%, respectively for A4 and A5). Although transport (A4) depends on specific conditions, it makes a considerable contribution to the impacts in the life cycle. This can be verified in the studies that analyze it. Stage A4 can contribute to the reduction of the total environmental load by selecting materials available close to the construction site.

The external walls with the best general environmental profiles were 1, 3, 5, 7, 10, 15, 17, and 20. Although all of the systems are relatively equivalent, the external walls that could be recommended as ideal are 7, 10, 3, 17, 1, and 5 (in decreasing order with respect to U-value) because they generate the lowest environmental load and have the best U-values. On the contrary, the most damaging combination of elements is that which includes an exterior small-format layer and an interior layer of LPB. The walls with this combination are 16, 19, and 8 (in increasing order of U-value).

This study leads to the conclusion that a selection of elements with better physical capacities can in turn generate a lower environmental load. Therefore, the selection of elements and materials will be a determining factor in environmental optimization.

In the design of the external walls (choice of materials), simple strategies have been established in order to reduce their environmental repercussions. These include the use of large-format pieces (mortar or clay), which reduce the quantity of materials that are needed for making the wall pieces and the binders used in their assembly (mor), and the controlled increase in the thickness of the thermal insulation. Although individually, the thermal insulation does have an important impact compared with the rest of the components, with regard to the external wall, this is moderate.

When making a comparison between the materials that make up each layer of the external wall, it was found that: (i) the exterior layers made with ceramic clay pieces are more harmful than those made of mortar pieces in CC (1.14) and ADP (1.5). On the contrary, the walls made with mortar pieces generate more HTP than those made with ceramic clay pieces (1.4); (ii) the interior layers made with LPB are more harmful than those made with ceramic clay pieces (HTP: 2.5, AP: 5.3, EP: 3.7), this value is 80% due to the galvanized steel profile; and (iii) the thermal insulations made from hydrocarbons are more harmful than those from natural wool in all of the categories (CC: 2.3, ADP: 3, AP: 1.15), except in HTP (3.4).

The prediction of the environmental behavior (simulation equation) allows the possible impacts that the external walls may generate in the product stage to be studied with facility. This provides a useful tool for those in charge of planning in the search for more environmentally-friendly options, without detriment to the performance of the components.

The sensitivity and uncertainty analysis indicate that stage A4 performs a significant role in reducing emissions within the cradle to handover life cycle. Also, further research studies could be done with a more robust sensitivity and uncertainty analysis to support the conclusions or implications of the present study.

Finally, as well as evaluating the data of the characterization of the model used, an analysis would be needed of the impact of each of the categories involved (but from a comparative perspective) to thereby establish the impact at different levels (national, European, or global). To achieve this, it would be necessary to carry out a normalization of the impact categories with updated impact data. Similarly, a weighting of each of the impact categories would be of interest for establishing the importance that the construction of different external walls has for them.

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Abbreviations

A1–A3	Product stage
A4	Transport from factory to site
A4–A5	Construction process stage
A5	Construction process/installation stage
ADP	Depletion of abiotic resources
CC	Climate change
CCP	Ceramic clay pieces
EL	Exterior layer
EP	Eutrophication potential
EPS	Expanded polystyrene
EW	External walls
G	Laminated plasterboard
GW	Glass wool

HBd	Double hollow brick
HBs	Single hollow brick
HR	Height of reference
HTP	Human toxicity
IL	Interior layer
LCA	Life cycle assessment
LCI	Life cycle inventory
LFP	Hollow large format
LFPp	Perforated large format partition wall
LPB	Laminated plasterboard
MB	Hollow mortar block
mor	Mortar
MP	Mortar pieces
ODP	Stratospheric ozone depletion
PB	Perforated brick
POCP	Photochemical oxidation
RW	Rock wool
SMB	Solid mortar brick
SPF	Spray Polyurethane Foam
TI	Thermal insulation
XPS	Extruded polystyrene

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ARTÍCULO 2:

Life Cycle Assessment of residential streets from the perspective of favouring the human scale and reducing motorized traffic flow. From cradle to handover approach

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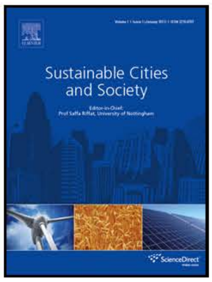

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Life Cycle Assessment of residential streets from the perspective of favoring the human scale and reducing motorized traffic flow. From cradle to handover approach

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HIGHLIGHTS

- The increase in the human scale and promoting non-motorized mobility in a residential Street (RS) generate lower environmental impacts (EI)
- Omitting a detailed analysis of the environmental consequences of material selection for a specific zone of RS may occasion significant EI
- The specific use of materials employed in the construction of the RS has a significant influence on the EI
- The use of granite should be limited in configuring and designing RS

- Applying the Life-Cycle Assessment (LCA) in the design phase can lead to a reduction in the EI generated in the production and construction stages of a RS
- The LCA acquires an important role in the design of the urban environment

ABSTRACT

Currently, few studies have compared the variations in environmental impact throughout the different stages of the life cycle of urban construction elements; and of these, only a minority approach it from the perspective of favoring mobility on a human scale and reducing the space allocated to motorized traffic flow.

This study, by means of quantitative data, shows the environmental implications associated with prioritizing the non-motorized mobility of a city's inhabitants during the design process of an urban construction element, the residential street (referring to the stages of the production and the construction process: the "cradle to handover" approach). An emerging methodology in urban themes was used in order to obtain the environmental analysis: Life Cycle Assessment (LCA).

The results show that the increase in the human scale and the favoring of non-motorized mobility generate a lower environmental impact (considering the same uses of materials for the different zones of analysis). Additionally, it was possible to establish the influence that the specific use of materials employed in the construction of the streets may have, as well as the importance that an LCA acquires in the design of the urban environment.

Keywords: Cradle to handover; Ecoindicator 99; Environmental impacts; Life cycle assessment; Non-motorized traffic flow; Pedestrian environment; Street design; Street materials; Urban planning.

1. Introduction

The street is one of the principal elements that define the configuration of the urban environment: "Streets lie at the heart of communities, shape human health and environmental quality, and serve as the foundation of urban economies. In many cities, streets make up more than 80% of all public space, and collectively have the potential to foster business activity" (GDCI & NACTO, 2016). Several researchers (Gilderbloom et al., 2015; Haider et al., 2018; Kwan & Hashim, 2016; Lindelöw et al., 2014) show the advantages that can accrue from an environment in which the human scale is prioritized during the design process of urban planning.

In recent years, aspects related to the analysis of streets, which favor a pedestrian environment over motorized traffic flow, have been studied and developed. Nevertheless, the majority of studies carried out focus exclusively on the usage stage, neglecting to use integral environmental data from the complete life cycle (Mendoza, Oliver-Solà, Gabarrel, Rieradevall, & Josa, 2012). If used, this data would allow the environmental load produced in the various stages of the life cycle of a specific street to be known from the design process.

Some of the studies which justify the consideration of environmental criteria (Araújo et al., 2014; Loijos et al., 2013; Mendoza, Oliver-Solà, Gabarrel, Rieradevall, & Josa, 2012; Noshadravan et al., 2013; Oliver-Solà et al., 2009) focus on comparisons and the exclusive implications involved in choosing the materials for a specific section of the street (usually sidewalks or travel lanes). However, from the perspective of favoring the human scale and reducing the space allocated to motorized traffic, no evidence has been found about the figures or proportions that show the possible environmental impact of the stages incorporated in the streets.

Therefore, the aim of this work is, using quantitative data, to show the environmental ramifications when priority is given to the inhabitants of a city during the design process of a street (referring to production and construction stages: the "cradle to handover" approach). To achieve this objective, a methodology has been used with which it is expected to obtain a greater perspective of its use in the urban environment: LCA.

The analysis compares the environmental behavior of 18 options that are grouped into three types of residential street sections: the conventional, favoring motor traffic flows, and two redesigned sections that prioritize the human scale and non-motorized traffic flows. All use the typical urban infrastructure building materials.

2. Method and data

2.1. Description of Life Cycle Assessment

2.1.1. Aim and scope

The defined aim of the LCA is to compare three street sections whose width varies as a result of favoring motorized and non-motorized flows, as well as the different materials they are made from. The aim of the study is to establish the possible environmental impacts generated by the different streets, in addition to finding the most environmentally suitable combination of materials and sections.

Previous works have related the "cradle to handover" perspective (or similar: "cradle to gate" and "cradle to site" (Malmqvist et al., 2018)) with the objective of providing information which contributes to defining the repercussions of the construction itself. Some recent manuscripts, which have considered these limits of the system, are listed in **Table 1**. In this sense, this research is a "cradle to handover" study –according to Annex 57 of the International Energy Agency (Seo et al., 2016)–, which includes the production stages: extraction of the raw materials (A1), transport (A2) and production of the materials (A3). It also includes the construction process stage, which is composed of: transport from production to the site (A4) as well as the building process itself (A5) – according to the Norm UNE-EN 15804 (AENOR, 2014)–. **Fig. 1** shows the analysis of the flow in the life cycle inventory (LCI) used in this study.

Additionally, according to the configurations established from the streets under study, the linear meter (ml) was the functional unit, since it is the one that best defines the evaluation of the environmental impacts of each integrated zone. Previous research (Moretti et al., 2018;

Petit-Boix et al., 2014) confirms that this functional unit is a reliable and objective parameter in this type of analysis. A constant total width of 13 meters was considered for the 18 options.

2.1.2. Data inventory

The Ecoinvent database, recognized internationally as a source of consistent and updated data (Frischknecht et al., 2007), was used to obtain the LCI. Applied to the field of research it mostly deals with information related to the European region, and it has been widely used in previous LCA studies (García-Guaita et al., 2018; Heinonen et al., 2016; Ortíz et al., 2010; Thiers & Peuportier, 2012).

The BEDEC materials database (ITEC, 2017) was used to quantify the materials and energy of the processes needed to develop stages A1-A5 of each street. The BEDEC database incorporates elements and construction materials of different types, whose technical characteristics belong in praxis to the Spanish ambit.

2.1.3. Impact assessment method and categories

The results of the environmental impact were processed using the Software LCA Manager 1.3 (Simpple, 2010), which allows the resources used and their environmental effects to be analyzed by means of the LCA methodology (AENOR, 2006). LCA Manager 1.3 has been used in previous research (Ortiz et al. 2010), with the results confirming its reliability.

The environmental impact method chosen was Ecoindicator 99, recognized as being one of the most used in performing the LCA. Ecoindicator 99 allows the environmental load of a product or process to be expressed as an individual score (Pré consultants, 2018). This method has been used in previous studies with reliable and comparable results (Biswas et al., 2017; Faludi et al., 2012; Kellenberger & Althaus, 2009; Pushkar, 2014; Sianipar & Dowaki, 2014). The included categories of environmental impact are of global interest and are grouped in the following areas of protection (AoP):

- Ecosystem quality(EQ): acidification-eutrophication, ecotoxicity and land occupation.
- Human health (HH): carcinogenics, climate change, ionizing radiation, ozone layer depletion and respiratory effects.
- Resources (RS): fossil fuels and mineral extraction.

2.2. Life cycle inventory

2.2.1. Production stages (A1-A3)

In the analysis of stages A1-A3, a study was made of all the materials of each street configuration that generated variations in the results. They were then used to conform the travel lane (TL), the pedestrian zone (PZ), the buffer zone (BZ) and the bicycle lane (BL), as well as the materials used in the lower layers (base and sub-base). The materials omitted from this study were those used for the curbs and those related to urban installations and fixtures (common elements in all the options studied, which do not show variations in the comparative analysis). The data for quantifying the materials was obtained from BEDEC and adapted to the characteristics of this study, for stages A1-A3 as well as for stage A5.

The streets are built of the typical inert materials most commonly used in construction. Most are petrous in origin: limestone, clays, sands, gravel, granites, and artificial and natural graded aggregates, among others; the exception is mastic asphalt, which contains the petroleum derivative bitumen. All of them are available as construction materials in Ecoinvent. The necessary quantity of each of these materials was obtained in order to make a linear meter of each option (1x13m), and then a waste coefficient (ITEC, 2017) was applied to them. **Table 2** shows the data used for the analyzed stages (A1-A3, and A4-A5) and the Ecoinvent datasets.

2.2.2. Construction process stages (A4-A5)

The transport from the factory to the site stage (A4) studies the impact connected with the operation (O_L in tkm) of the transport vehicle used, by means **Eq. (1)**.

$$O_L = WD \tag{1}$$

Where W is the weight required by the functional unit for each material used in making the street; D is the distance from the factory to the roadworks. The average distance from a minimum of two factories to the final reference point (the theoretical center of Barcelona city, Plaza Cataluña) was evaluated as D. The values of D were obtained using Google Maps as a georeferencing system and were as follows: 60 km for aggregates, 40 km for concrete and granite slabs, 20 km for cement, concrete and asphalt. The lorry chosen for the transport complied with all the specifications of weight and maximum size for short journeys, as established by the Spanish Ministry of Development (Ministerio de Fomento, 2017).

The usage share of the machinery (PU_M, **Eq. (2)**) was evaluated for the construction process stage (A5), as well as the operating energy (E_O in kg of diesel or kWh, as the case may be) of the machinery used in building each option **(Eq. (3))**.

$$PU_M = (TU/UL_M) \tag{2}$$

$$E_O = TU \, x \, P_M \tag{3}$$

Where TU is the usage time of each machine; UL_M is the useful life of the machine equal to 10,000 h (Frischknecht et al., 2007); and P_M can be either the fuel or the machine's potency, depending on the situation; the machinery's consumption needs are shown in **Table 3**.

2.3. Case studies description

Three types of sections (**Fig. 2**) were designed, referring to types of secondary streets for a residential area (GDCI & NACTO, 2016); one conventional (CO) and two redesigned (RA and RB). Each study section can be described as follows: (i) in the reference case CO, priority is given to the TL for motorized vehicular traffic, while the pavements (PZ and BZ) comply with the minimum widths recommended by the Global Designing Cities Initiative (GDCI) and the National Association of City Transportation Officials (NACTO). (ii) In the RA case, emphasis is laid on increasing the widths of PZ and BZ, and the space dedicated to motorized traffic flow is composed of a TL and a parking lane (PL). Finally, (iii) the section of the RB cases is designed to be as respectful as possible to the alternatives to motorized transport. In this last case, unlike the others, only one TL is included; and so the areas dedicated to PZ, including the BL in both directions, are increased.

By means of alterations in their constituent materials, the three sections to be studied were also evaluated to determine the environmental effects they might provoke. The materials used were of the type commonly used as street components in European urban environments: two for TL (asphalt and concrete); three for PZ (asphalt, concrete slabs and granite slabs); two for (asphalt and concrete) and finally, one for BZ (silica sand). **Fig. 3** details the design composition of each material variation used, all satisfying the established requirements for their application (Alabern i Valentí & Guilemany i Casadamon, 1999; M

The combination of the three types of section and the different materials produces 18 different case studies (**Table 4**).

The information in table 4 is organized into six comparative groups (**Table 5**) taking into account the similarity of the materials used for each section. This was done with the aim of comparing the environmental consequences of increasing the percentage aimed at the human scale in a specific residential street, without the differences in materials being a factor of variability.

3. Results and discussion

In this study it was found that prioritizing the human scale leads to a reduction in the environmental impact, as long as conventional materials such as concrete and asphalt are used in configuring residential streets. In the graphs of the comparative groups C1-C4 (**Fig. 4**), it can be seen that an 11.54% increase in the areas destined for human scale (RA cases) may generate reductions of between 6.94% (C-4) and 11.09% (C-2). Meanwhile, an increase of 30.77% (including 18% of the space destined for BL) may generate reductions of between 9.49% (C-4) and 22.27% (C-2) in the total environmental impact (RB cases).

Fig. 4 also shows that, unlike the results of the C1-C4 groups, the use of granite increases the environmental impact even when the human scale is favored. For instance, if the RA sections are used, the environmental impact is increased by 4.61% in C-5 and 6.85% in C-6; in the case of the RB sections the increases are 9.26% in C-5 and 14.90% in C-6, all in respect of the CO sections. This shows that the use of granite (as well as its production) generates important environmental issues and therefore, as there are alternative materials with equivalent functional and service capacities, the use of granite should be limited in configuring residential streets.

A comparison is made in **Fig. 5** between cases 11 of the RA and 17 of the RB, the cases with the best general environmental performance, and the six design cases CO (1-6). From this comparison it can be deduced that they establish a reductive environmental impact, which (i) ranges from 7.88% (case 5) to 76.50% (case 3) with regard to case 11; and (ii) from 11.44% (case 5) to 77.40% (case 3) with regard to case 17. Additionally, comparing the RA and RB, the section that incentivizes greater non-motorized traffic flows (case 17; including BL) shows the best environmental behavior, reducing impacts by 3.86%. This is congruent with Gehl's research (Gehl, 2010): "The desire for a healthy city is strengthened dramatically if walking or biking can be a natural part of the patterns of daily activities".

Similarly, the results of the case studies show the influence that the definition of the materials used in making the streets has; the use of granite in PZ (average of C5-C6) produces noticeable variations regarding the behavior of the cases in which it is not used (average of C1-C4), increasing the total impact by 270% (**Fig. 6**). Previous studies have also shown that granite generates higher environmental loads in comparison to other materials used in urban infrastructure (Mendoza, Oliver-Solà, Gabarrel, Josa & Rieradevall, 2012; Mendoza, Oliver-Solà, Gabarrel, Rieradevall & Josa, 2012).

Additionally, when comparing the cases that only used asphalt and concrete as materials in all sections of the street (**Fig. 6** and **Table 6**), it was seen that they affected each of the AoP differently except for EQ, where the variation is reduced (2%) in comparison with RS and HH. Concrete generates 73% more impact on HH, with its most important categories being the impact on climate change and its respiratory and carcinogenic side effects, which respectively produce 113%, 51% and 70% more impact than asphalt. Asphalt has a greater impact on the RS, generating 121% more fossil fuel consumption. Some authors agree with the previously established data, for example (Mendoza, Oliver-Solà, Gabarrel, Rieradevall & Josa, 2012) discovered that the primary energy demand of asphalt is higher than that of concrete, but its contribution to global warming is lower.

In the street sections where asphalt was used, the most affected AoP is RS (>70%), whereas for concrete and granite it is HH (≈50%, ≈70%, respectively, **Fig. 6**). These environmental implications occur in more than 80% of the A1-A3 stages (greater environmental implication); therefore, their influence will define and establish the complete environmental profile of each street, as has also been shown in previous studies (Cass & Mukherjee, 2011).

In this study (**Table 7**), A1-A3 represents ≈85% for the cases C1-C4 and ≈96% for the cases of C5-C6, followed by A4 with ≈15% for C1-C4 and ≈4% for C5-C6; finally, there is A5, with less than 3% in all the cases. Although each study is limited by its own conditions, it is important for similar research to consider the "cradle to handover" approach; despite the discrepancies that may arise due to these conditions, the extent of the A4-A5 stages' environmental impact should not be underestimated, as other studies have also concluded (Kellenberger & Althaus,

By emphasizing the weight of each of the categories evaluated by the Ecoindicator 99 (**Fig. 7**), it was found that the greatest impact of the materials used was on the exhaustion of fossil fuel supplies, respiratory disorders and climate change. Regarding asphalt, more than 72% of the impact is due to fossil fuel consumption (RS), 13.53% to respiratory side effects and 6.33% to climate change. As it is a petrol derivative, it is considered a non-renewable source. Previous research (Araújo et al., 2014) indicates that the most obvious impact of paving materials is their consumption of natural resources.

In **Fig. 7**, it can also be seen that 42.48% of concrete's environmental impact corresponds to the exhaustion of fossil fuels, 26.58% to respiratory side effects, 17.60% to climate change and 5.18% to carcinogenic effects. The use of fossil fuels is linked to the high temperatures needed in cement production. The emission of particles and volatile elements, such as mercury, is also an inherent part of this industry (Bustillo-Revuelta, 2008) (impact on HH). Previous research has shown that concrete is an important contributor to climate change (Venkatarama Reddy & Jagadish, 2003), due mainly to the GHGs generated by the chemical reactions in clinker production (Damtoft et al., 2008).

Finally, the impact categories most affected by the use of granite (whether combined with asphalt or concrete) are respiratory effects, with almost 60%, climate change with 5%, carcinogenic effects with 3.7% (HH) and fossil fuel consumption (RS) with 26% (**Fig. 7**). Previous studies have attributed the environmental load of human toxicity to the stainless steel used in saw blades, due to their chromium content. Similarly, it has been found that the granite related processes emit significant quantities of GHGs (even more than concrete and asphalt) (Mendoza, Oliver-Solà, Gabarrel, Josa & Rieradevall, 2012).

4. Conclusions

The main findings of this research are as follows. (i) Giving priority to the human scale and promoting non-motorized traffic flow when configuring a residential street can lead to a reduction in the environmental impact generated by the production and construction stages. (ii) It confirms that omitting a detailed analysis of the environmental consequences of material selection for a specific section of street may occasion significant environmental effects. (iii) Applying the LCA in the design phase can lead to a reduction in the environmental effects generated in the production and construction stages of a residential street.

Knowing the impact generated in the production and construction stages of a residential street designed on a human scale, compared with a street that prioritizes motorized traffic (as well as the impact generated by varying the building materials in each zone), It will reinforce the priority (widely demonstrated in the usage stage) by developing a residential street design oriented towards achieving a pedestrian environment. Likewise, the consequences of choosing specific materials are also shown. Obtaining this will be a further step towards developing more sustainable cities.

Despite the previous guidelines, the use of materials such as granite generates increases in environmental impact of up to 14.9% for a linear meter of PZ, even when an environment favoring the human scale is prioritized. However, using conventional materials such as concrete and asphalt can generate reductions from 11% (increasing to 11.5% PZ+BF) to 22.27% (increasing to 31% PZ+BZ+BL). If the three analyzed materials are compared, granite generates 270% more environmental damage than concrete and asphalt. The last two, although they have similar general consequences, occasionally show different effects in each of the impact categories studied. For instance, asphalt consumes 121% more fossil fuels than concrete, which for its part causes 73% more harm to human health (producing 113%, 51% and 79% more climate change, respiratory and carcinogenic effects than asphalt).

Finally, it is essential to carry out more analysis such as this, which will include different typologies as well as a wider study of alternative materials (among which, those reincorporated in the life cycle); this will lead to LCA becoming an integral feature of the construction industry with regard to the process of urban planning.

5. Future scope

After analyzing the environmental advantages of the increase in non-motorized flows (cradle to labor approach), it is expected to include other variables to be developed in the future of this research; for example, to evaluate the influence of the properties of materials on the potential of reducing environmental burdens throughout the all life cycle. Previous research indicates the advantages that concrete can have over the asphalt in aspects such as the reduction of heat island and energy demand in urban environments (Akpinar & Sevin, 2018a, 2018b). Besides that, the concrete also has greater durability, which foresees that it will require less maintenance and repair (stage of use of LCA) (Mendoza, Oliver-Solà, Gabarrel, Rieradevall & Josa, 2012).

On the other hand, conditions such as the radioactivity generated by the granite (EPA, 2018), the potential capacity of reincorporation of each material that is used, or the possible variation that the reduction of the motorized flow would exert in the results (e.g., traffic speed) would be appropriate to be considered.

All the above aspects would allow the obtaining of general arguments regarding the promotion of mobility in the human scale and the reduction of the space destined for motorized flow in residential streets.

Declarations of interest: none.

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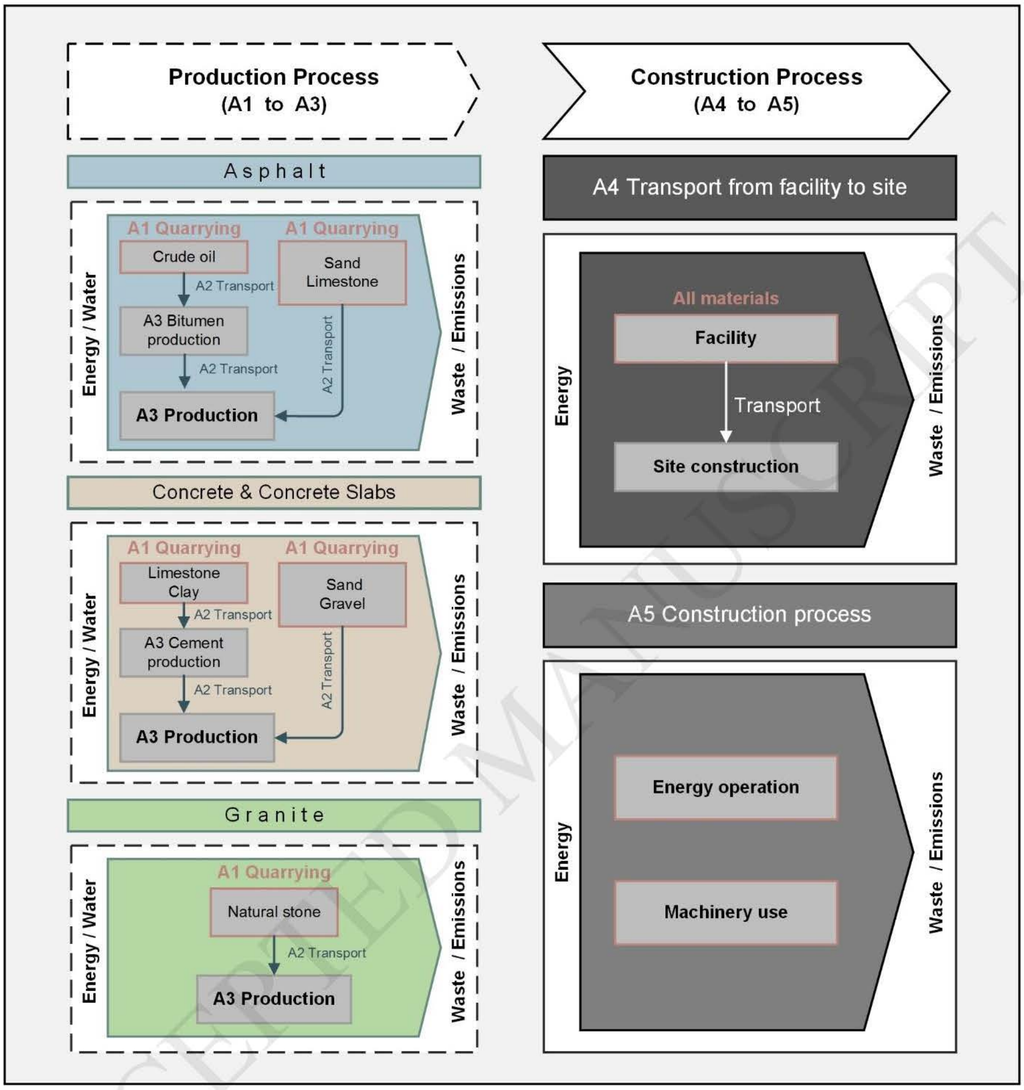

Fig. 1. Flowchart of the LCI.

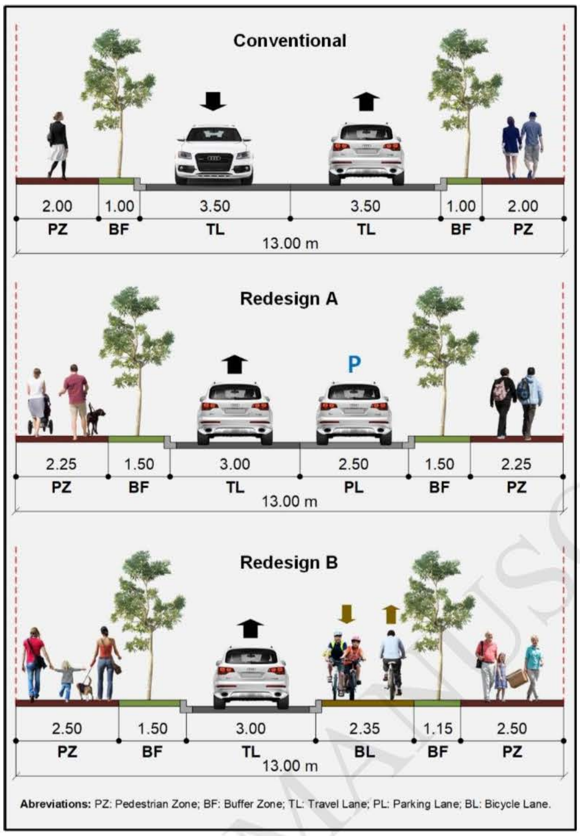

Fig. 2. Street sections (CO, RA y RB).

AC, 2018).

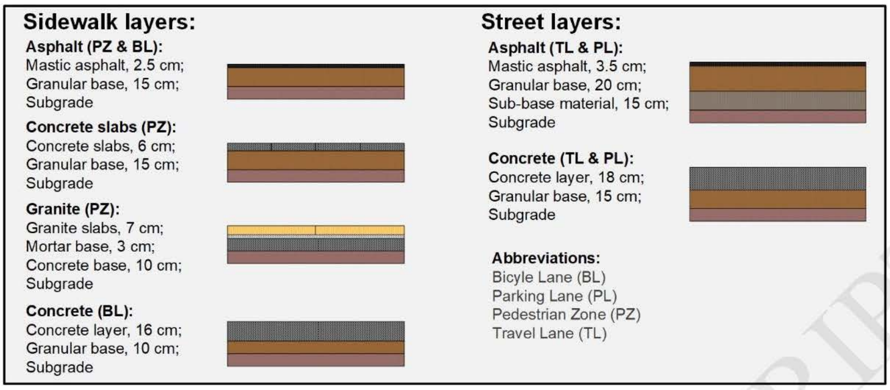

Fig. 3. Detail of surfaces for TL, PZ and BL.

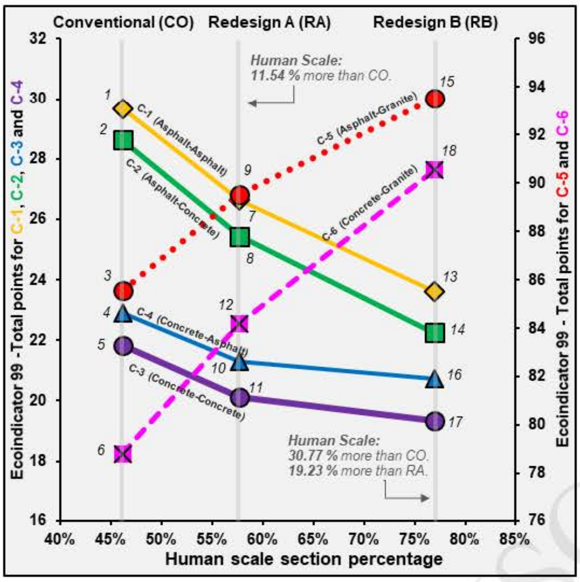

Fig. 4. Comparisons between cases showing similar ratios of materials.

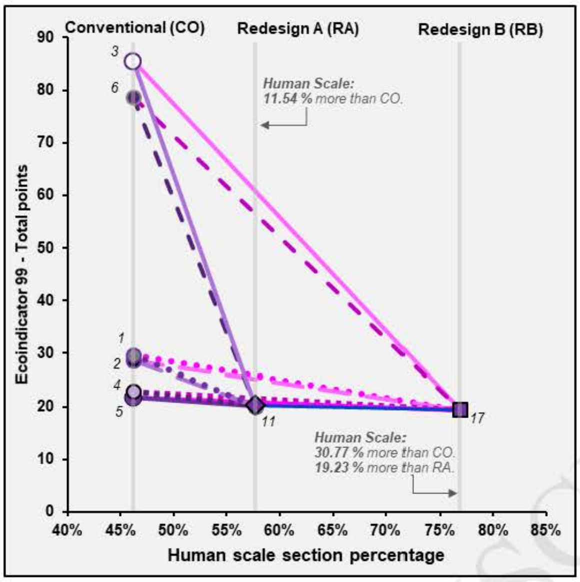

Fig. 5. Comparison of the CO cases (1-6) with those that produce less environmental impact in RA (11) and RB (17).

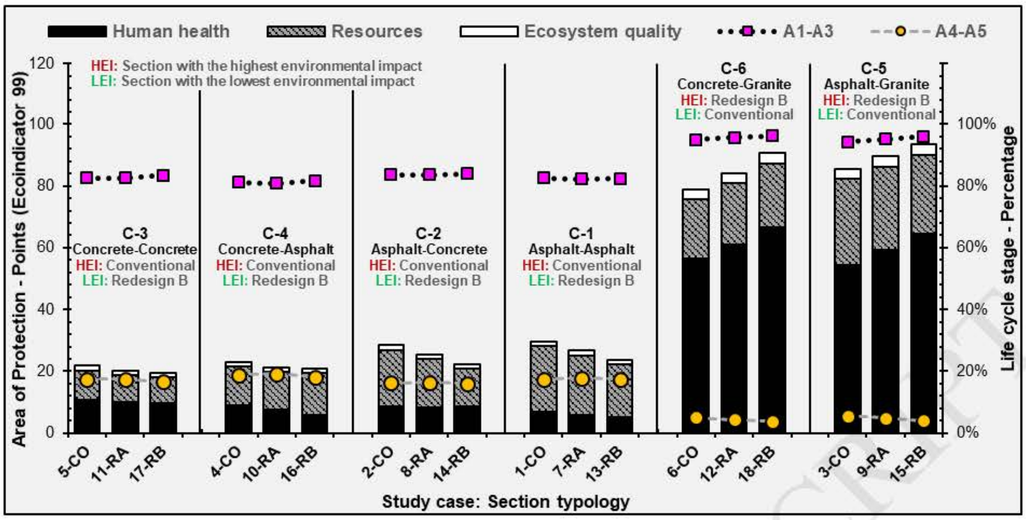

Fig. 6. Comparisons of the cases showing similar ratios of materials used.

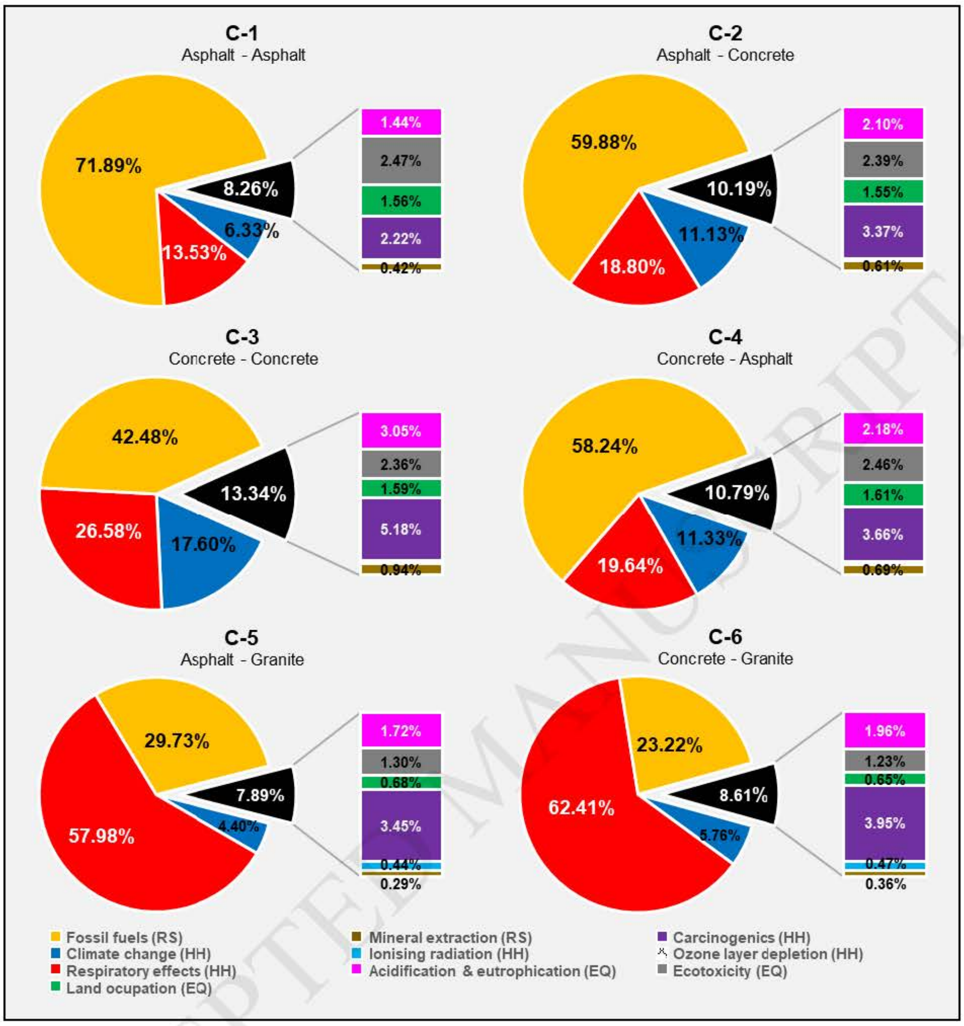

Fig. 7. Percentage corresponding to each impact category, according to the average results of each comparison.

Table 1

LCA studies that consider the stages directly related to the construction process.

Stage	Authors	Highlights
Cradle to gate (A1-A3)	(Cass & Mukherjee, 2011)	Development of a method that quantifies pavement life cycle emissions.
	(Moretti et al., 2018)	Analysis of environmental impacts of two types of road cross-sections.
	(Sandanayake et al., 2018)	Comparison of greenhouse gas (GHG) emissions and energy consumption in wood and concrete buildings.
Cradle to site (A1-A3+A4)	(Gardezi et al., 2016)	Development of an embodied carbon prediction tool for conventional housing.
Cradle to handover (A1-A3+A4-A5)	(Smith & Durham, 2016)	Environmental evaluation of pavements considering economic, environmental and mechanical performance criteria.
	(Mohajerani et al., 2018)	Evaluation of the impacts generated by the incorporation of biosolids in conventional materials.

Table 2

LCI for functional unit (one linear meter) of each street zone.

Stage	Material/process	Conventional					Redesign A					Redesign B							Ecoinvent material/process
		TL Asphalt	TL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	TL + PL Asphalt	TL + PL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	TL Asphalt	TL Concrete	PZ + BZ Asphalt	PZ +BZ Concrete	PZ +BZ Granite	BL Asphalt	BL Concrete	
A1 - A3	Water (kg)	89.78	60.38	34.50	-	25.20	70.54	47.44	38.81	-	28.35	38.48	25.88	43.13	-	31.50	18.11	12.08	Tap water, at user
	Coarse aggregates (ton)	3.98	2.05	1.17	-	-	3.13	1.61	1.32	-	-	1.71	0.88	1.47	-	-	0.62	410.55	Gravel, crushed, at mine
	Cement (kg)	129.65	-	-	-	31.50	101.87	-	-	-	35.44	55.57	-	-	-	39.38	-	-	Portland cement, strength class Z 42.5, at plant
	Concrete base (m^3)	-	-	-	0.42	0.42	-	-	-	0.47	0.47	-	-	-	0.53	0.53	-	-	Concrete, normal, at plant
	Fine aggregates (kg)	-	-	-	24.81	205.38	-	-	-	27.91	231.05	-	-	-	31.01	256.73	-	-	Silica sand, at plant
	Asphalt (kg)	540.23	-	220.50	-	-	424.46	-	248.06	-	-	231.53	-	275.63	-	-	115.76	-	Mastic asphalt, at plant
	Concrete/concrete slabs (m^3)	-	1.32	-	0.33	-	-	1.04	-	0.37	-	-	0.57	-	0.41	-	-	0.35	Concrete, exacting, at plant
	Granite slabs (kg)	-	-	-	-	742.56	-	-	-	-	835.38	-	-	-	-	928.20	-	-	Natural stone plate, polished, at regional storage
	Sand (kg) for BZ	-	-	444.00	473.60	444.00	-	-	744.00	793.60	744.00	-	-	714.00	875.60	714.00	-	-	Silica sand, at plant
A4	Operation lorry (tkm)	253.40	181.38	101.87	77.11	87.78	199.10	142.51	129.27	102.39	113.42	108.60	77.73	136.88	113.40	119.26	39.50	41.71	Transport, lorry 16-32t, EURO5
A5	Machinery E10-6 (unit)	20.56	38.80	7.65	0.65	8.82	16.15	30.49	8.61	0.73	9.92	8.81	16.63	9.56	0.82	11.03	4.02	9.54	Building machine
	Energy (kg)	2.38	2.46	0.86	0.01	-	1.87	1.93	0.97	0.01	-	1.02	1.06	1.07	0.01	-	0.45	0.57	Diesel, at regional storage
	Energy (kWh)	-	-	-	-	0.06	-	-	-	-	0.07	-	-	-	-	0.08	-	-	Electricity, low voltage, production ES, at grid / ES

Table 3

Fuel consumption or potency of machinery.

Machine	Fuel consumption (kg/h) or potency (kW)
Tanker truck 10 m^3	8.3
Vibratory roller	10.8
Motor Grader	14.1
Dumper	2.2
Asphalt paver	8.7
Concrete paver	11.4
Vibrating tray	1.2
Concrete mixer	0.7

Table 4

Case studies description.

Typology	Case	Zone - Total Width (m) – Material	Most common material in: MF[A] zones – GM[B] zones
Conventional	1	TL-7.00-Asphalt; PZ-4.00-Asphalt; BZ-2.00-Sand	Asphalt - Asphalt
	2	TL-7.00-Asphalt; PZ-4.00-Concrete; BZ-2.00-Sand	Asphalt - Concrete
	3	TL-7.00-Asphalt; PZ-4.00-Granite; BZ-2.00-Sand	Asphalt - Granite
	4	TL-7.00-Concrete; PZ-4.00-Asphalt; BZ-2.00-Sand	Concrete - Asphalt
	5	TL-7.00-Concrete; PZ-4.00-Concrete; BZ-2.00-Sand	Concrete - Concrete
	6	TL-7.00-Concrete; PZ-4.00-Granite; BZ-2.00-Sand	Concrete - Granite
Redesign A	7	TL & PL-5.50-Asphalt; PZ-4.50-Asphalt; BZ-3.00-Sand	Asphalt - Asphalt
	8	TL & PL-5.50-Asphalt; PZ-4.50-Concrete; BZ-3.00-Sand	Asphalt - Concrete
	9	TL & PL-5.50-Asphalt; PZ-4.50-Granite; BZ-3.00-Sand	Asphalt - Granite
	10	TL & PL-5.50-Concrete; PZ-4.50-Asphalt; BZ-3.00-Sand	Concrete - Asphalt
	11	TL & PL-5.50-Concrete; PZ-4.50-Concrete; BZ-3.00-Sand	Concrete - Concrete
	12	TL & PL-5.50-Concrete; PZ-4.50-Granite; BZ-3.00-Sand	Concrete - Granite
Redesign B	13	TL-3.00-Asphalt; PZ-5.00-Asphalt; BL-2.35-Asphalt; BZ-2.65-Sand	Asphalt - Asphalt
	14	TL-3.00-Asphalt; PZ-5.00-Concrete; BL-2.35-Concrete; BZ-2.65-Sand	Asphalt - Concrete
	15	TL-3.00-Asphalt; PZ-5.00-Granite; BL-2.35-Asphalt; BZ-2.65-Sand	Asphalt - Granite
	16	TL-3.00-Concrete; PZ-5.00-Asphalt; BL-2.35-Asphalt; BZ-2.65-Sand	Concrete - Asphalt
	17	TL-3.00-Concrete; PZ-5.00-Concrete; BL-2.35-Concrete; BZ-2.65-Sand	Concrete - Concrete
	18	TL-3.00-Concrete; PZ-5.00-Granite; BLss-2.35-Concrete; BZ-2.65-Sand	Concrete - Granite

[A]Motorized flow; TL & PL [B]Green mobility; PZ & BL.

Table 5

Comparatives showing similar ratios of materials.

Comparative	Most common material in: MF[A] zones – GM[B] zones	Case – Section typology
C-1	Asphalt – Asphalt	1-CO ; 7-RA ; 13-RB
C-2	Asphalt - Concrete	2-CO ; 8-RA ; 14-RB
C-3	Concrete - Concrete	5-CO ; 11-RA ; 17-RB
C-4	Concrete - Asphalt	4-CO ; 10-RA ; 16-RB
C-5	Asphalt - Granite	3-CO ; 9-RA ; 15-RB
C-6	Concrete - Granite	6-CO ; 12-RA ; 18-RB

[A]Motorized flow; TL & PL [B]Green mobility; PZ & BL.

Table 6

Values of Ecoindicator 99 for the most important impact categories for concrete and asphalt.

Impact Category	C-1 (Concrete)	C-3 (Asphalt)
Carcinogenic	1.06	0.59
Climate change	3.60	1.69
Respiratory effects	5.43	3.60
Fossil fuels	8.68	19.16
Total	20.43	26.65

2009).

Table 7

Values of Ecoindicator 99 for the AoP of the life cycle stages.

	Asphalt (C-1)			Concrete & Asphalt (C2&C4)			Concrete (C-3)			Granite (C5&C6)		
Area of protection	A1-A3	A4	A5	A1-A3	A4	A5	A1-A3	A4	A5	A1-A3	A4	A5
Ecosystem quality	1.14	0.30	0.02	1.17	0.26	0.02	1.19	0.22	0.02	3.01	0.26	0.02
Human health	4.64	1.20	0.08	6.90	1.05	0.07	9.16	0.90	0.07	59.22	1.05	0.07
Resources	16.17	2.58	0.51	11.37	2.26	0.44	6.57	1.93	0.37	20.79	2.25	0.36
Stage representativeness (%)	84%	16%	2%	85%	15%	2%	85%	15%	2%	96%	4%	1%

ARTÍCULO 3:

Environmental Challenges in the Residential Sector: Life Cycle Assessment of Mexican Social Housing

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Environmental Challenges in the Residential Sector: Life Cycle Assessment of Mexican Social Housing

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Abstract: Social Housing (SH) in Mexico has a potentially important role in reducing both the emission of greenhouse gases and the use of non-renewable resources, two of the main challenges facing not only Mexico but the planet as a whole. This work assesses the environmental impact generated by the embodied stages of a typical SH throughout its life cycle (cradle to grave), by means of a Life Cycle Assessment (LCA). Two types of envelope and interior walls and three types of windows are compared. It was found that SH emits 309 kg CO_2 eq/m^2 and consumes 3911 MJ eq/m^2 in the product stages (A1 to A3) and construction process (A4 to A5); the most important stages are those referring to the products, namely, A1 to A3, B4 (replacement) and B2 (maintenance). Additionally, benefits were found in the use of lightweight and thermal materials, such as concrete blocks lightened with pumice or windows made of PVC or wood. Although the use of LCA is incipient in the housing and construction sector in Mexico, this work shows how its application is not only feasible but recommended as it may become a basic tool in the search for sustainability.

Keywords: life cycle assessment; social housing; embodied stages; embodied energy; embodied greenhouse gases; residential sector; Latin America and the Caribbean

1. Introduction

The population of Latin America and the Caribbean (LAC) represents 8.55% of the world population [1], of which 75% is concentrated in countries with emerging economies (32% Brazil, 20% Mexico, and 22% for Colombia, Argentina, Peru and, Chile together) [1,2]. The high metabolic rates of this region have obliged governments to design and introduce new approaches to separate their economic growth from the use of resources and, consequently, their environmental impact [3].

Although the LAC countries have twice the population of the United States (U.S.), they produce a lower global warming effect. This is similar to the case of the Asian giants, where India emits just 24% of the Greenhouse Gases (GHG) produced by China, despite each being home to 18% of the world's population. Regarding energy consumption, the USA, the European Union (EU), and China consume 4.15, 1.89, and 1.26 times more than the world per capita average respectively, while India and LAC consume 3.88 and 1.47 times less (Table 1). This indicates that the environmental impact indices generated by each country (and region) are discordant with the number of people living in them.

Table 1. Global basic indicators. Data from: [1,4–9].

Country/ Region	Total Population (People) [1]	Urban Population (%) [4]	CO_2 Emissions (%) [5]	CO_2 eq Emissions (%) [6]	Energy Consumption (kwh/Capita) [7]	Population Growth (Annual %) [8]	Household Size (People) [9]
China	1,386,395,000	58	28.27	23.27	3927	0.6	3.4
India	1,339,180,127	34	5.69	5.61	805	1.1	4.6
U.S	325,719,178	82	14.43	11.85	12,984	0.7	2.5
EU	512,461,290	75	9.85	8.78	5908	0.2	-
LAC	644,137,666	80	5.21	10.74	2129	1.0	-
World	7,530,360,149	55	100	100.00	3127	1.2	-

The emerging economies of LAC must face up to important environmental challenges in order to avoid replicating the throwaway society model of the industrialized nations [10]. Among the most important problems is the rise in annual temperature caused by the increase of GHGs and the wasteful consumption of energy (from renewable and non-renewable sources); there are also the residues generated by this consumption, such as Construction and Demolition Waste (CDW) and Municipal Solid Waste (MSW), which play an important part due to the quantities involved.

To overcome their own environmental challenges, LAC countries need to set up schemes to achieve economic and social growth that will avoid unsustainable environmental damage, that is, plans in line with the objectives of the new sustainable development agenda, which are governed by three cardinal axes: Eradicating poverty, protecting the planet, and ensuring prosperity for all [11].

Mexico has the second largest population of the countries in LAC, with more than 129 million inhabitants (80% concentrated in urban areas) [1]. Over the last ten years it has had economic growth of 2.2% [12] and, up to 2017, annual population increase of 1.3% [8] (Table 2); therefore, an increase in energy needs and consumption of natural resources can be expected in coming years, as well as GHG emissions and the CDW and MSW that generate them.

Table 2. Basic indicators in LAC. Data from: [1,4–9].

Country/ Region	Total Population (People) [1]	Urban Population (%) [4]	CO_2 Emissions (%) [5]	CO_2 eq Emissions (%) [6]	Energy Consumption (kwh/Capita) [7]	Population Growth [6] (Annual %) [8]	Household Size (People) [9]
Argentina	44,271,041	92	10.7	6.6	3052	1.0	3.3
Brazil	209,288,278	86	27.7	52.0	2601	0.8	3.3
Chile	18,054,726	87	4.3	2.1	3912	0.8	3.6
Colombia	49,065,615	80	4.4	3.0	1290	0.8	3.5
Mexico	129,163,276	80	25.1	11.5	2090	1.3	3.7
Peru	32,165,485	78	3.2	1.3	1308	1.2	3.8
LAC	644,137,666	80	100	100	2129	1.0	-

2. Environmental Challenges in Mexico

In Mexico, the national inventory of greenhouse gases and compounds is closely linked to scientific and technical criteria established by the Intergovernmental Panel on Climate Change (IPCC). It reported that in 2015 a total of 683 million tons (Gg) of CO_2 eq were emitted, of which 71% were Carbon Dioxide (CO_2) and 21% Methane (CH_4). The inventory also counted 148 Gg absorbed by vegetation (mainly forest and jungle), bringing the net emissions balance to 535 Gg of CO_2 eq (Table 3). Additionally, 1.4% of the total CO_2 and 1.24% of the total CO_2 eq in the world was generated in 2012 (in the LAC group, only surpassed by Brazil) (Table 2).

Table 3. National inventory of greenhouse emissions and compounds. Data from: [13].

Category	Net Emissions Gg CO_2 eq	Total Emissions Gg CO_2 eq
1 Energy	480,878.831	480,878.831
2 Industrial processes and use of products	54,111.761	54,111.761
3 Agriculture, forestry and other land uses	−46,286.569	102,059.499
4 Residues	45,909.010	45,909.010
Total	534,613.033	682,959.101

Of all the emissions (Figure 1), the housing sector emits 3.1% of CO_2 eq, derived from compounds of CO_2, CH_4 and Nitrous Oxide (N_2O) generated by the consumption of natural gas, liquid petroleum gas, kerosene and diesel; there is also CH_4 and N_2O due to the burning of firewood in homes, the emissions generated by their operational energy. Other emissions related to the residential sector are those caused by the energy needed for transport (25.1%) and the construction and manufacturing industry (9.3%); the mineral and metal industries (5.5%) and the elimination of solid waste (3.2%). However, the corresponding proportional part of each must be obtained. It is essential to analyze exhaustively the GHGs that generate the activities that are carried out throughout the life cycle of the residential sector, especially social housing. Which, due to its high representation (88%) in the homes of the country, is a dominant relevance.

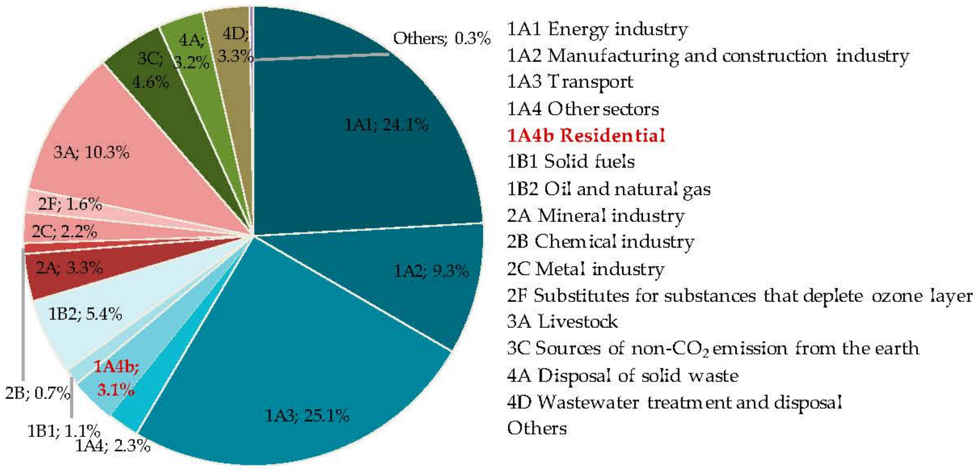

Figure 1. National inventory of greenhouse gas emissions and compounds. Data from: [13].

Moreover, in 2017, Mexico ranked 16th in the list of countries with the highest energy consumption in the world, reporting the third consecutive year with an energy independence index equivalent to 0.76; that is, 24% less energy was produced than necessary for the various consumption activities within the national territory [14]. This is despite the country's wealth of natural resources such as gas, coal and renewable energy sources (water, wind, solar and marine energy); however, its economy and energy supply are dependent on fossil fuels, which together with the lack of energy planning is a major cause for concern [15].

The national energy balance in 2017 (Figure 2), shows that the national energy consumption for this year was 9249.75 Petajoules (PJ), of which the 58% corresponding to total energy consumption and 32% to activities inherent to the energy sector (transformation, own consumption, and losses) stand out (Figure 2a). The total energy consumption (Figure 2b) in this year was 5362.8 PJ, which is attributed to the internal market or the productive activities of the national economy, of which the housing sector is responsible for 14%, due to the operating requirements of housing [14]. Additionally, other data needed for this sector is that referring to the proportional part of transport (44%) and industry (35%).

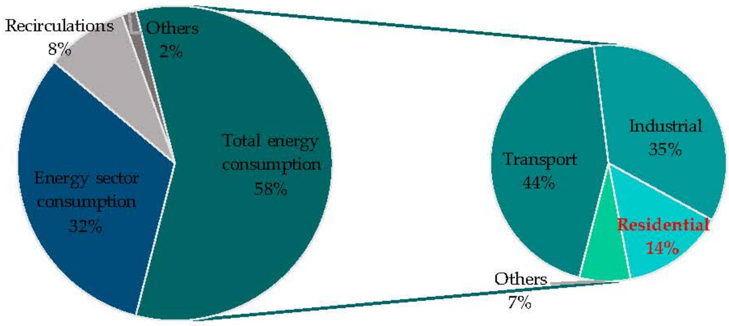

Figure 2. (**a**) National energy consumption: 9249.75 PJ; (**b**) Total energy consumption: 5362.8 PJ. Data from: [14].

Regarding the waste products (Table 4), Mexico generates 0.4% of the world total of CDW and 3.4% of the MSW (second in the LAC region), and although the sum of its waste is lower than that of countries such as China (1,130,000,000 t CDW; 328,922,213 t MSW), U.S (548,000,000 t CDW; 240,380,753 t MSW) and India (530,000,000 t CDW), the impact on a national scale should not be ignored as it has limited management protocols and lacks the infrastructure for waste processing [16].

Of the CDW generated in public and private works, 20% is disposed of in authorized dumps and only 3% is recycled; the rest is used in site levelling, landfills and, inappropriately, in road or street repairs [16]. In this respect, the NOM-161-SEMARNAT-2011 norm came into effect in 2013, stating that construction waste shall be classified as special handling waste, requiring action to be taken for its reuse and recycling or, where appropriate, for its proper disposal [17]. In the case of the 44 million MSW generated annually [18], despite having the General Law for the Prevention and Management of Waste, only 84% are collected, 78.5% are dumped in final disposal sites, and only 9.6% are recycled [19].

Table 4. CDW and MSW. Data from: [18,20–24].

Country	CDW [20]	MSW	MSW
Region	**(t/Year)**	**(t/Year)**	**(kg/Capita.Year)**
Brazil	70,000,000	79,900,000 [21]	382 [21]
China	1,130,000,000	328,922,214 [24]	237 [24]
India	530,000,000	90,000,000 [23]	67 [23]
México	12,000,000	44,432,167 [18]	344 [18]
U.S.	519,000,000	240,380,753 [18]	738 [18]
EU	830,000,000	247,518,803 [18]	483 [18]
LAC	-	131,000,000 [22]	203 [22]
World	3,000,000,000	1,300,000,000 [24]	173 [24]

2.1. *Life Cycle Assessment in Mexico*

Various methods have been used in recent decades to measure the environmental performance of human and natural activities. One of these is the Life Cycle Assessment (LCA). "LCA, has become a key methodology to evaluate the environmental performance of products, services and processes and it is considered a powerful tool for decision makers" [25]. In Mexico, the LCA was used for the first time in the late 1990s and early 2000s, in a study on waste management carried out by the National Institute of Ecology and Climate [26]. The methodology has been used in several economic sectors in the country, such as the energy [27] or mining industries [28]. According to the study conducted by Valdivia, until 2014 Mexico was the second ranking LAC country in terms of publications referring to LCA (101 articles) [3].

Until 2010 research using LCA had a preferential focus on waste management issues; from that year onwards, studies focused on topics such as the energy sector, the analysis of carbon and water footprints and the construction sector [26]. Within the latter, studies have been carried out on the co-processing of municipal waste used as fuel for a cement kiln [29], as well as the publication of a book on LCA in construction, where topics such as social housing (SH) are analyzed [30].

The housing sector began to attract attention in 2006, when the government introduced life cycle thinking into the National Housing Law [31]. In this respect, Cerón-Palma et al. (2013) measured the Global Warming Potential (GWP) of the operating energy of a SH [32]; as well as proposing strategies to reduce energy demand [33], other studies have focused on optimizing rainwater [34,35]. In addition to the LCA, other tools such as the Building Sustainability Rating Systems [36] and product environmental statements [31,37] have been used.

Although in Mexico the use of LCA in the construction and residential sector is basically nil, its application is feasible and can become a valuable tool in the search for environmental solutions as it has been in various regions of the world [38].

2.2. *Housing in Mexico*

Housing types in Mexico are classified according to their constructed surface: Economic (30 m^2), popular (42.5 m^2), and traditional (62.5 m^2), known together as SH. There are also medium (97.5 m^2), residential (145 m^2), and residential plus (225 m^2) [39]. In the last five years, more than 2.58 million housing units have been built, of which 88% are SH (11% economic, 47% popular, 30% traditional), while the remaining 12% corresponds to the medium, residential and residential plus models [40]. It is estimated that 600,000 new housing units will be needed annually during the next decade [41].

Due to the high representation of the SH, the National Development Plan 2013–2018 has promoted the issue of sustainable construction in this sector [31]. As a result, in the last decade, Mexico has stood out among the middle-high income level countries due to its Finance Program for Housing Solutions, which aims to provide more sustainable SH. These actions have been considered exemplary with respect to global good practices [36].

According to data compiled up to 2010 by the National Housing Commission (CONAVI), 86% of the housing stock is in use (80.12% permanent use and 5.65% temporary use), while 14% is unoccupied [42]. Until 2015, the inventory of occupied housing showed 31,949,709 private units with an average of 3.7 habitants each [43]; of these, 73% are single-family, 19% are two-family, and 7% are multifamily housing. Multifamily housing is mainly concentrated in the states with the highest population density of the Republic (41% in Mexico City, 15% Mexico State, 7% in Jalisco and 5% in Puebla), while it is practically nil in the rest of the country (an average of 1% per state) due to the persistence of the single-family dwelling [44].

Housing in Mexico has great challenges to face; on the one hand, there are impacts generated throughout its use, and on the other hand, there are environmental impacts arising from the incorporated stages of materials and processes necessary for construction. National inventories of energy and greenhouse gases and compounds have clearly established the impacts generated by the residential sector in its operation (B6, Operational energy [45]); however, it is necessary to define the environmental burdens that are generated from the incorporated activities of its life cycle to consider a "from the cradle to the grave" approach.

2.3. *Objectives of the Study*

The objectives of this research are (1) to identify the state of the most relevant environmental impacts occurring in Mexico, emphasizing the residential sector, and (2) to achieve an approximation of the environmental impacts generated by this sector. To reach the latter objective, an LCA methodology applied to a representative SH of the Mexican ambit will be used; the elements that make up its envelope will be varied, resulting in a total of six options to be analyzed throughout its life cycle.

3. Materials and Methods

3.1. Goal and Scope of the LCA

The objective of the LCA was to establish the environmental impacts generated by a typical SH in Mexico throughout its life cycle. For the analysis the constructive elements that make up the structure, the envelope (opaque and transparent parts) and the internal partitions were considered, as well as their basic finishes. Previous studies have analyzed the structure, the envelope [46–50] and the interior walls [51,52] of a building because of their contribution to the total environmental loads generated by their incorporated stages and also because of the impact these elements (especially the envelope) have on the energy performance of the building's operational stage.

The reference dwelling is a built and practical prototype in the Mexican ambit; five additional alternatives are proposed by varying interchangeable and feasible materials and construction solutions in the local practices. Of the six options to be analyzed, all have in common the structure (consisting of foundation slabs, columns and beams of reinforced concrete, and roof slab of reinforced concrete lightened with Expanded Polystyrene Pieces, EPS), the exterior and interior wooden doors, and the basic finishes (1.5 cm thick mortar for exterior and interior walls, 1.5 cm thick plaster for roof slab, and vinyl paint for all cases). The elements that differed were the exterior and interior walls (two types of concrete pieces: (1) Hollow Block of $12 \times 20 \times 40$ Filled with Expanded Perlite (PE) and (2) Solid Partition of Lightened Concrete with Pumice Aggregates of $10 \times 14 \times 28$ (PU)) and windows (three types: Aluminum (AL), PVC (PV) or Wood (WO)). The nomenclature used is shown in Figure 3.

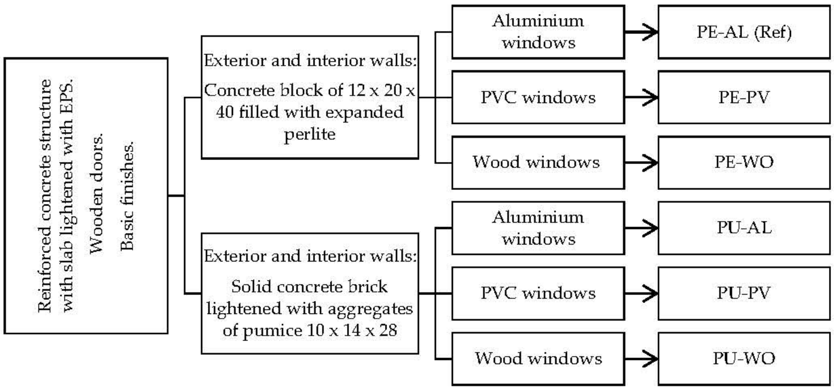

Figure 3. Nomenclature and elements of the options analyzed.

The basic characteristics of the structure are illustrated in Figure 4, and Figure 5 shows the configuration of the exterior and interior walls, as well as the location and dimensions of the doors and windows of the SH.

The established functional unit was the 42 m^2 dwelling (Figure 5), with a useful life of 50 years according to previous research [53–56]. Its dimensions correspond to those of popular housing, which is nationally the most representative (47% which, together with the traditional and economic housing, makes up 88% of the SH [40]). The analyzed elements allow an approximate estimate of the environmental impact generated by a Mexican SH in all stages of its life cycle; in addition, any changes of the proposed elements are required to be equivalent with respect to their thermal, structural, and functional capacities, thus allowing for their possible comparison and the best environmental choice.

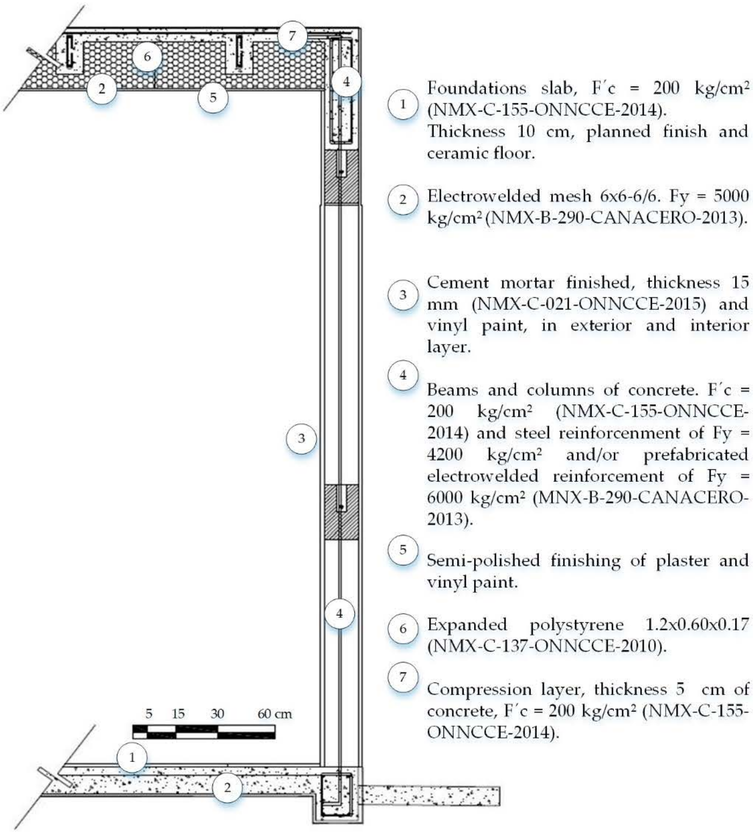

Figure 4. Cross section of basic characteristics of the structure.

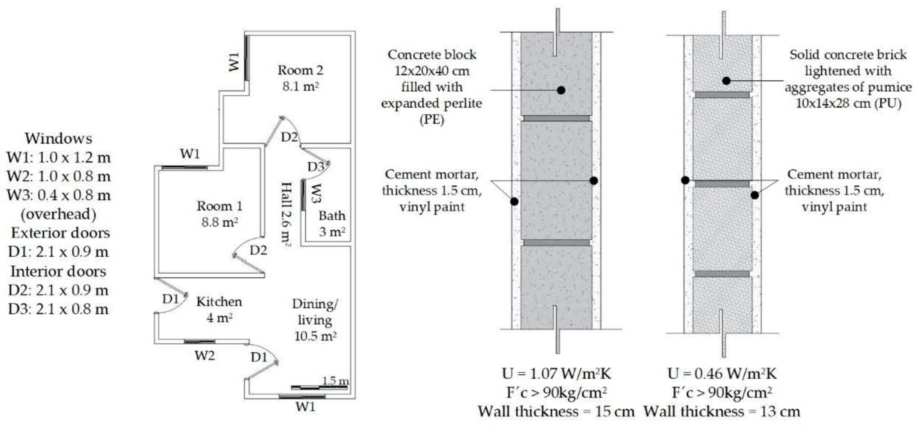

Figure 5. Social housing area, dimensions of doors and windows, and configuration of the exterior and interior walls.

Despite the initiatives of CONAVI aimed at the construction of sustainable housing and related programs, it has not yet been possible to comply with the regulations on energy efficiency in SH; however, these efforts have led to the search for solutions and practices that show a continual improvement, as reported in previous studies [36]. The walls of the reference prototype are one example of this. They have eco-technology used in SH (expanded perlite insulation to fill the concrete blocks, with a thermal conductivity coefficient (λ) of 0.042 W/mK); however, its Thermal Transmittance (U), equal to 1.07 W/m^{2}K, does not comply with NOM-020-2011 (U = 0.476 W/m^{2}K for cities with extremely hot climates to U = 0.909 W/m^{2}K for cities with temperate-cold climates [57]). Therefore, the construction of concrete walls lightened with pumice aggregates (λ = 0.052 W/mK) was proposed, with similar characteristics of functionality and compressive strength (13 cm thick, F´c > 90 kg/cm^2), but with improved thermal performance due to the intrinsic properties of the material. This results in walls with a U equal to 0.46 W/m^{2}K (complying with NOM-020-2011 for the least favorable case; Figure 5).

3.2. Boundaries and Functional Unit

The analysis considered the Stages of Product (A1 to A3) and Construction Process (A4 to A5); Maintenance (B2) and Replacement (B4), Demolition (C1), Transport (C2) and Disposal (C4). The Use (B1), Repair (B3), and Refurbishment (B5) stages were excluded, being considered dependent on the user; Waste Processing (C3) was also omitted as immediate dumping is the single most used scenario in the Mexican context [16]. The analysis may be considered cradle to grave, according to the proposal of annex 57 of the IEA EBC for evaluating the incorporated energy and the CO_2 eq emissions. Annex 57 complements the international ISO 21931-1 and European EN 15978 standards for the evaluation of building structures to improve transparency for the multiple stakeholders in the LCA process [58]. The limits of the LCA system are shown in Figure 6.

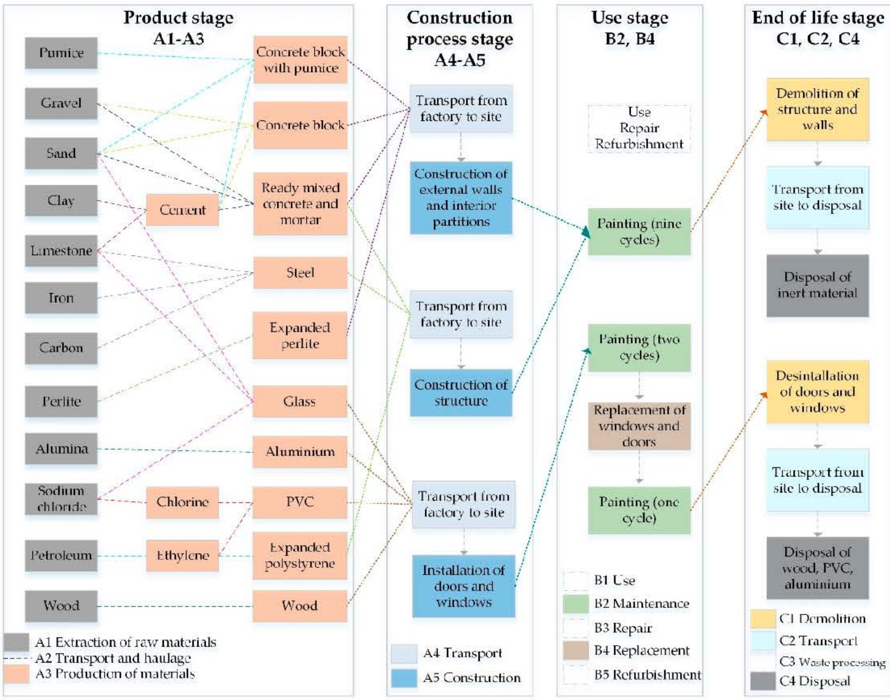

Figure 6. The life cycle of SH in Mexico.

3.3. Life Cycle Inventory

Two databases were used, one specializing in the quantification of materials and construction processes at the Mexican level, CYPE [59], and another specializing in life cycle inventories, ecoinvent 3.1 (2014) [60]. However, since ecoinvent initially included products and activities exclusively at the

European—in particular the Swiss—level, recent versions incorporate global, and sometimes specific, processes from countries outside Europe, as in the case of Mexico or North America. Previous studies conducted in Mexico using ecoinvent have obtained favorable results [29,32,61–64]; and although their use might presuppose a limitation, this is in turn an available tool that generates reliable approaches to environmental impacts.

3.3.1. Product Stage (A1 to A3)

The product stage included the manufacture of the structure, the envelope, the internal partitions, and the basic finishes. The weights obtained from the inventory were also considered with a 5% waste rate. The required quantities of each material used and the corresponding dataset are shown in Table 5. The processes and materials used (taken from ecoinvent) were adapted to the conditions of the SH; however, in the specific case of the windows (AL, PV, and WO), the dataset analyzed represents a more efficient window than those used for the SH; although the weights and dimensions were adapted to the conditions of the project, in the case of these elements, it is prudent to consider the results as values of close environmental impact.

Table 5. Inventory of materials of the product stage.

Element	Material	Quantity	Ecoinvent Dataset [1]
Structure	Concrete (m^3)	13.8	Concrete production 20 MPa, RNA only, RoW
	Steel (kg)	975.4	Reinforcing steel production, RoW
	EPS (kg)	193.1	Polystyrene foam slab production, RoW
	Block (kg)	1869.0	Concrete block production, RoW
	Mortar (kg)	211.8	Cement mortar production, RoW
	Water (m^3)	0.05	Tap water production, conventional treatment, RoW
	Ceramic tile (kg)	776.3	Ceramic tile production, RoW
	Cement (kg)	316.9	Cement production, Portland, RoW
	Plaster (kg)	633.8	Stucco production, RoW
Doors	Exterior doors (m^2)	3.8	Door production, outer, wood-glass, RoW
	Interior doors (m^2)	5.5	Door production, inner, wood, RoW
PE wall	Block 12 × 20 × 40 (kg)	12,199.5	Concrete block production, RoW
	Mortar (kg)	6638.5	Cement mortar production, RoW
	Water (m^3)	0.3	Tap water production, conventional treatment, RoW
	Expanded perlite (kg)	196.8	Expanded perlite production, RoW
	Vinyl paint (kg)	24.3	Alkyd paint production, white, water-based, product in 60% solution state, RoW
PU wall	Pumice block (kg)	8155.9	Lightweight concrete block production, pumice, RoW
	Water (m^3)	0.3	Tap water production, conventional treatment, RoW
	Mortar (kg)	6941.9	Cement mortar production, RoW
	Vinyl paint (kg)	19.7	Alkyd paint production, white, water-based, product in 60% solution state, RoW
Windows	Aluminum-window (m^2)	0.8	Market for window frame, aluminum, U = 1.6 W/m^2K, GLO [2]
	PVC-window (m^2)	0.8	Market for window frame, poly vinyl chloride, U = 1.6 W/m^2K, GLO [2]
	Wood-window (m^2)	0.8	Market for window frame, wood, U = 1.5 W/m^2K, GLO [2]
	Glazing 3 mm (kg)	2.4	Market for glazing, double, U < 1.1 W/m^2K, GLO

[1] RNA: Northern America; RoW: Rest of the World; GLO: Global. [2] Its characteristics correspond to a window with measurements of 1.6 × 1.3 m, with frame visible area ≈ 0.5 m^2, and U value of 1.6 W/m^2K, weight per m^2 of frame visible area of 50.7 kg for aluminum, 94.5 kg for PVC and, 80.2 kg for wood.

3.3.2. Construction Process Stage (A4 to A5)

In Mexico the greatest impact on the demand for electricity in homes occurs in the northern and coastal areas of the country—warm climates—where the use of cooling equipment is more common than heating equipment [57]; therefore, for better representativeness, the analyzed SH is assumed to be located in the Northwest of Mexico, using in this work the proposed alternative that satisfies the most unfavorable U-value corresponding to the cities of Hermosillo, Guaymas, and Mexicali (0.476 W/m^2K).

The environmental impact generated by a truck operating with a load capacity of 7.5–16 t, measured in Tons-kilometers (tkm), was determined for a complete travel cycle (round trip) of the material. The maximum dimensions of the truck correspond to those established by the communications and transport secretariat for long distance roads ET-A (maximum load of 17.5 t) and for short distance roads D (maximum load of 11 t) and Euro 4 engine [65].

The values considered for the distances travelled were an average of the journeys between the hypothetical center of each capital of the north-western states of the country (Baja California, Baja California Sur, Chihuahua, Durango, Sinaloa, and Sonora) and the nearest factories of each type of material previously established in the inventory (determined using Google maps). The resulting values were: 15 km for concrete, steel, EPS, doors, and windows; 20 km for vinyl paint; 400 km for ceramic floors; 470 km for steel; and 510 km for expanded perlite (methodology used in previous studies [66,67]). The quantities required for each construction alternative are shown in Table 6.

Table 6. Inventory of processes of transport from factory to site (A4).

Process	PE-AL	PE-PV	PE-WO	PU-AL	PU-PV	PU-WO	Ecoinvent Dataset
Lorry operation (tkm)	3454	3455	3455	3141	3142	3142	Transport, freight, lorry 7.5–16 metric ton, EURO4

For the assessment of the Construction Stage (A5), the processes and materials necessary for the formwork of the structure (with wood and steel) were considered, as well as those for the transport, discharge, and vibration of the concrete used in the structure and for mixing the mortar used in the walls. The quantities used are shown in Table 7.

Table 7. Inventory of materials/processes of the construction process (A5).

Element	Material/Process	Use Time	Ecoinvent Dataset [1]
Formwork of the structure	Steel (kg)	37.51	Reinforcing steel production, RoW
	Wood (m^3)	0.23	Sawnwood production, softwood, kiln dried, planed, RoW
PE alternatives	Potency less than 18 kW (h)	8.73	Machine operation, diesel, <18.64 kW, steady-state, GLO
	Potency greater than 75 kW (h)	1.76	Machine operation, diesel, ≥74.57 kW, steady-state, GLO
PU alternatives	Potency less than 18 kW (h)	9.01	Machine operation, diesel, <18.64 kW, steady-state, GLO
	Potency greater than 75 kW (h)	1.76	Machine operation, diesel, ≥74.57 kW, steady-state, GLO

[1] RoW: Rest of the World; GLO: Global.

3.3.3. Use Stage (B2, B4)

Of the stage of use, those stages corresponding to the useful life of each material during the building's 50 years of useful life were considered, that is, the Maintenance (B2) and the Replacement (B4) of the elements. The maintenance intervals and replacement cycles obtained from the literature are shown in Table 8.

The elements that needed Maintenance (B2) were the doors, the windows (painting every ten years = 3 cycles) and the walls (painting every five years = 9 cycles). In the Replacement stage (B4), the doors and windows are the elements with a useful life less than the SH, and so their replacement is considered at 30 years (one replacement cycle in the total timeline of the SH). The quantities required are listed in Table 9.

Table 8. Maintenance intervals and replacement cycles for SH elements. Data from: [54,55,68–72].

Element	Useful Life (Years)	Activity Maintenance	Maintenance Cycle	Replacement Cycle
Reinforced concrete structure	50 [68]	-	-	-
External and internal walls	>50 [69,70]	-	-	-
Ceramic tiles	50 [68]	-	-	-
Interior and exterior doors	30 [55,71]	Paint every 10 years [54]	3	1
Windows	30 [54]	Paint every 10 years [54]	3	1
Vinyl paint	5 [72]	Paint every 5 years	9	-

Table 9. Inventory of materials/processes of maintenance and replacement.

Stage	Element	Quantity	Ecoinvent Dataset
B2	Paint doors (kg)	5.94	Alkyd paint production, white, water-based, product in 60% solution state, RoW [1]
	Paint windows WO (kg)	0.52	Alkyd paint production, white, water-based, product in 60% solution state, RoW [1]
	Paint walls (kg)	218.25	Alkyd paint production, white, water-based, product in 60% solution state, RoW [1]
	Transport for WO (PE/PU, tkm)	8.99	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Transport for AL-PV (PE/PU, tkm)	8.97	Transport, freight, lorry 7.5–16 metric ton, EURO4
B4	Exterior doors (m^2)	3.8	Door production, outer, wood-glass, RoW [1]
	Interior doors (m^2)	5.5	Door production, inner, wood, RoW [1]
	Aluminum windows (m^2)	0.8	Market for window frame, aluminum, U = 1.6 W/m^2K, GLO [1]
	PVC windows (m^2)	0.8	Market for window frame, poly vinyl chloride, U = 1.6 W/m^2K, GLO [1]
	Wood windows (m^2)	0.8	Market for window frame, wood, U = 1.5 W/m^2K, GLO [1]
	Glazing 3 mm (kg)	2.4	Market for glazing, double, U < 1.1 W/m^2K, GLO [1]

[1] RoW: Rest of the World; GLO: Global.

3.3.4. End of Life Stage (C1, C2, C4)

The CDW management scenarios in Mexico are limited by the scarcity or even lack of infrastructure. There is only one CDW recycling plant in the whole country, in Mexico City (Recycled concretes); nevertheless, this is a pioneering initiative not only in Mexico but also in the LAC region [73]. The NOM-161-2011 [74] sets out the requirements for special waste management (where the CDW are included) and is obligatory for large-scale generators of waste (>80 m^3).

In this sense, at the end of life stage, the energy required for the operation of the demolition equipment of the structure and walls (C1) of the SH (pneumatic hammer, cutting equipment, and portable compressor) was considered. Subsequently, the effect of the operation of the transport truck (C2) was obtained by the same process previously established in A4. The average distance between the hypothetical center of each reference city to the dump was 30 km. Finally, the total amount of CDW generated by SH was calculated to obtain the impact of its landfill disposal (C4) (processing in a recycling plant being currently impossible). The materials used were considered inert, as being of petrous, metallic, and petroleum origin, so their processing did not pose a potential risk. The quantities are shown in Table 10.

Table 10. Inventory of materials/processes of the end of life. Data from: [60].

Stage	Process	Quantity	Ecoinvent Dataset
C1	Use time PE alternatives (h)	187.54	Machine operation, diesel, <18.64 kW, steady-state, GLO [1]
	Use time PU alternatives (h)	185.33	Machine operation, diesel, <18.64 kW, steady-state, GLO [1]
C2	Lorry operation PE-AL (tkm)	3477.44	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PE-PV (tkm)	3479.56	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PE-WO (tkm)	3478.87	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PU-AL (tkm)	3241.22	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PU-PV (tkm)	3243.34	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PU-WO (tkm)	3242.64	Transport, freight, lorry 7.5–16 metric ton, EURO4
C4	Inert waste PE-AL (kg)	57,319.06	Treatment of inert waste, inert material landfill, RoW [1,2]
	Inert waste PE-PV (kg)	57,957.34	Treatment of inert waste, inert material landfill, RoW [1,2]
	Inert waste PE-WO (kg)	57,992.62	Treatment of inert waste, inert material landfill, RoW [1,2]
	Inert waste PU-AL (kg)	54,020.30	Treatment of inert waste, inert material landfill, RoW [1,2]
	Inert waste PU-PV (kg)	54,055.59	Treatment of inert waste, inert material landfill, RoW [1,2]
	Inert waste PU-WO (kg)	54,044.07	Treatment of inert waste, inert material landfill, RoW [1,2]

[1] RoW: Rest of the World; GLO: Global. [2] Module Treatment of inert waste, inert material landfill, RoW, contains exchanges to process-specific burdens (energy, land use) and infrastructure.

3.4. Environmental Impact Assessment

More than 40% of world energy consumption and 30% of the GHGs can be attributed to the construction industry [58]. Therefore, both effects measured in their respective impact categories have been considered inherent to this sector and have been addressed in previous investigations [75–79]. In this sense, the categories of impact selected for analysis in this study are those referring to energy and embodied emissions of SH, which are climate change and embodied energy. Additionally, to complete the information, two more categories have been chosen, which like the previously mentioned have been considered to have a global effect: Human toxicity and Abiotic Depletion Potential (ADP). The environmental impact methods used were, therefore, IPCC 2013 for the GWP (climate change), Cumulative Energy Demand (CED, for embodied energy), and CML 2001 for Human Toxicity Potential (HTP) and ADP.

4. Results

The analyzed SH generates an environmental burden (including all the stages of A to C) of 17 t CO_2 eq, 252.5 Gigajoules (GJ) eq, 104.3 kg antimony eq, and 9.4 t Paradichlorobenzene (1,4-DCB) eq (average of the six options). Of these, just the construction of the SH (finished product A1 to A5) generates a load of 13 t CO_2 eq, 165 GJ eq, 71 kg antimony eq, and 7 t 1,4-DCB eq (Table 11), i.e., more than 70% of the average impacts of all the categories analyzed when the embodied stages of the life cycle are considered.

Table 11. Impacts generated by the SH in stages A, B, and C.

Impact Category[1]	PE-AL			PE-PV			PE-WO			PU-AL			PU-PV			PU-WO			AVERAGE		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
GWP	13.3	2.5	1.7	13.0	2.2	1.7	12.9	2.1	1.7	13.3	2.5	1.6	13.0	2.2	1.6	12.9	2.1	1.6	13.1	2.3	1.7
EE	170	54	35	167	51	35	168	53	35	164	54	34	161	51	34	162	53	34	165	53	34.4
ADP	73.7	19.6	15.6	71.9	17.8	15.6	70.9	16.9	15.6	71.3	19.6	14.9	69.4	17.8	14.9	68.5	16.9	14.9	71.0	18.1	15.3
HTP	7.9	2.7	0.5	6.8	1.6	0.5	6.8	1.6	0.5	7.6	2.7	0.5	6.6	1.6	0.5	6.5	1.6	0.5	7.0	2.0	0.5

[1] GWP: t CO_2 eq; EE: GJ eq; ADP: kg antimony eq; HTP: t 1,4-DCB-Eq.

The product stage is established as that of greatest contribution (A1 to A3: 57% CED, 61% ADP, 71% HTP-GWP), followed by that of replacement (B4: 6% GWP, 8% ADP, 12% CED, 15% HTP) and maintenance (B2: 6% HTP, 7% GWP, 9% ADP-CED); it is therefore established that the stages with greater environmental effects are those involving finished products (A1 to A3, B2 and B4: 78% CED-ADP; 85% GWP; 91% HTP), in this case, those used in constructing the building, the paint for its maintenance, and the replaceable objects (windows and doors). Meanwhile, the stages referring to the processes produce significantly less effect; from greater to lesser, they are those relating to transport (A4 + C2: 3.3% HTP, 7.7% GWP, 9.3% CED, 10.1% ADP), to construction/demolition (A5-C1: 3.7% HTP, 6.1% GWP, 7.6% ADP, 9% CED), and lastly, to their final disposition (C4: 1.5% GWP, 1.6% HTP, 3.7% CED and 3.9% ADP) (Figure 7).

Previous research has dealt with the embodied impacts of a building (or its elements), studying different stages such as A1 to A4 [80], A1 to A5 [66,79,81], A and C [51] and A to C [48,49,82,83]; similar to this study, these works found that the greatest environmental detriment occurs in stage A1 to A3, with values ranging from 85% to 99% for those who evaluated up to A1 to A5 [51,66,79–81] and from 60% to 80% for those who evaluated the complete cycle (A to C) [48,49,82,83]. For the rest of the stages, the results depended on the different criteria established in each study, so there are still discrepancies in the results obtained. Nevertheless, the data obtained in this work is found within the previously reported intervals; for example, the studies that evaluated B1-B5 reported values ranging from 11% to 25% [48,49], those that studied A4, from 1% to 9% [51,66,79–81], those that evaluated A5 from 1% to 8% [49,51,66,79–81], while those that studied the C stages showed intervals from 1% to 3% [48,51] up to 23% [49], this stage showing the most variation.

Figure 7 shows how the greater variability occurs when a wood or PVC window is changed to aluminum for the HTP, going from 11–12% to 19% of the total damage. This can be attributed to the high amounts of contamination produced in the aluminum production process, which includes substances such as CO_2, Sulfur Dioxide (SO_2), Polycyclic Aromatic Hydrocarbons (HAP), Perfluorocarbons (PFC), Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) [84]. Similar to the study by Yasantha et al. (2007), where it was found that although wooden windows have a better environmental (and economic) performance, aluminum windows were preferred socially [85].

On the other hand, the damage caused by A1 to A3 is more evident for the GWP (70–72%), which is because the most representative materials used in the SH (concrete, steel, ceramic pieces, mortar) are linked with the emission of GHGs [13,66,67,86], due to the chemical reactions in their manufacturing processes and the high content of carbonates in their basic components, such as limestone or clay [87,88]. The greatest variation found in the impact categories was in stage A1 to A3, with a difference of 14% between the GWP (72%) and the CED (58%). This difference in the representation of the CED is spread over the rest of the stages, above all in B4 and B2 (because the manufacture of paint and window materials is more closely linked to energy consumption [86,89] than to GHG emissions) and in A5 and C1 (for the energy used by the machinery).

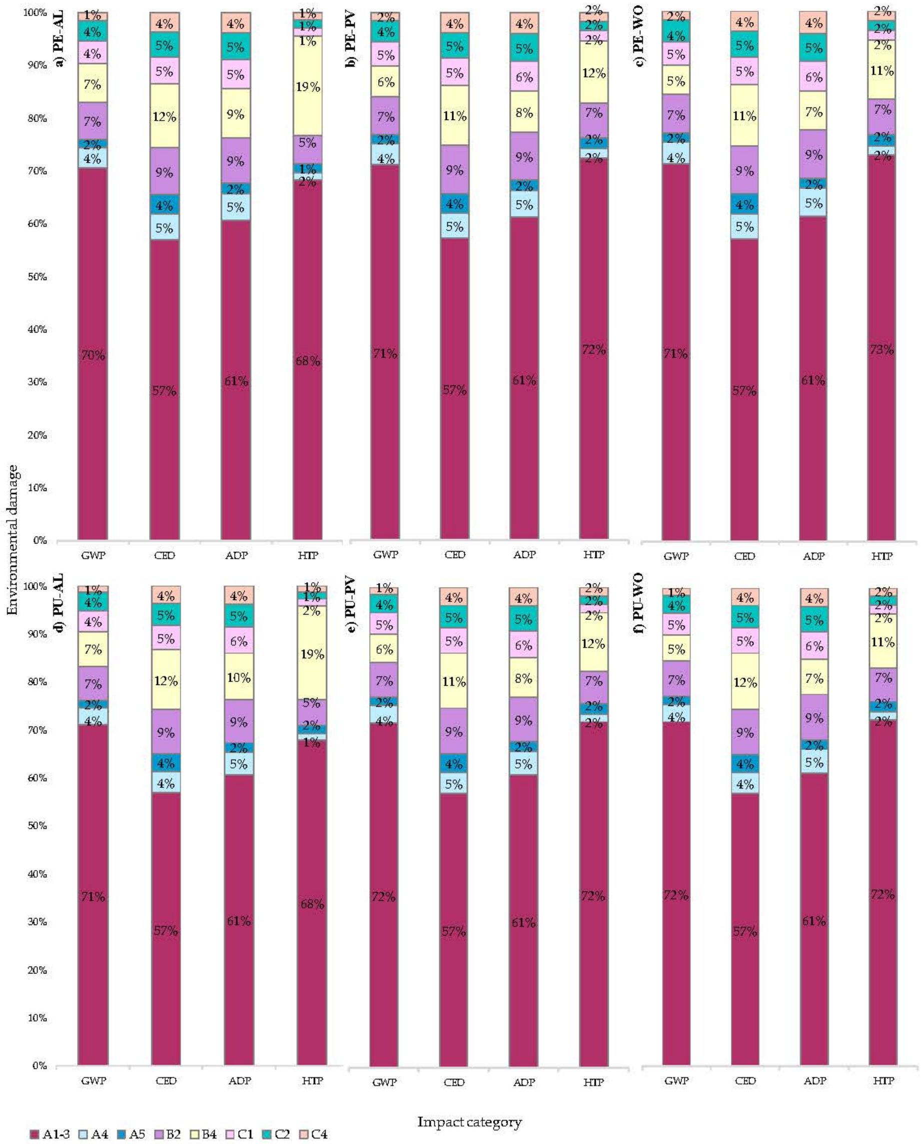

Figure 7. Percentage of environmental damage generated by each stage analyzed in the entire life cycle for: (**a**) PE-AL, (**b**) PE-PV, (**c**) PE-WO, (**d**) PU-AL, (**e**) PU-PV and, (**f**) PU-WO.

Analyzing each impact category separately (Figure 8), it was seen that the least favorable option in all cases was that of the reference (PE-AL), which is more pronounced in the stages A1 to A3 and B4. Previous studies have found that the production of aluminum (stages A1 to A3 or B4) requires high energy consumption [89], up to six times that of steel per unit of weight [86], as well as the inherent contaminants [84]. Therefore, the least favorable of the six combinations analyzed is that which includes heavy material with a moderate load potential and light material with a high load potential.

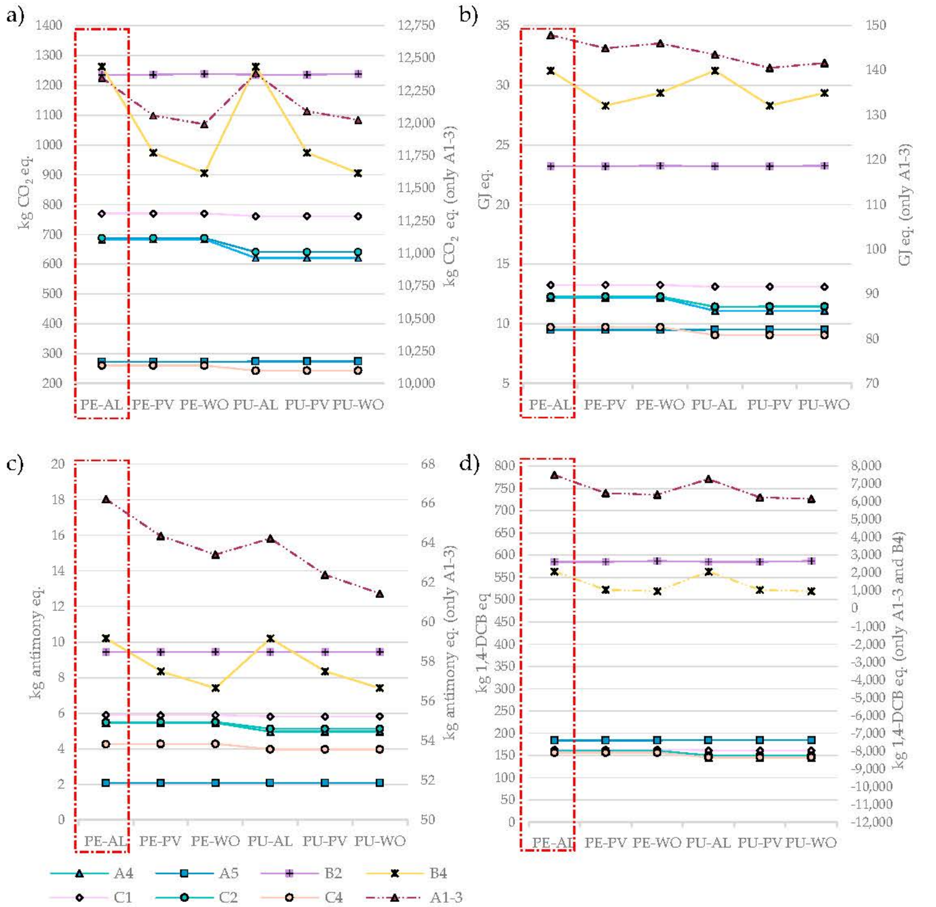

Figure 8. Environmental damage generated by each stage analyzed of the six alternatives of SH in the four impact categories: (**a**) GWP, (**b**) CED, (**c**) ADP and, (**d**) HTP.

Furthermore, when the stages with higher variability are discarded (A1 to A3 and B4, Figure 8), it can be seen that the options using PU are more favorable than those using PE, which can be attributed to the fact that the pumice aggregates are lighter than the conventional ones [90]. This coincides with previous research that recommends the use of volcanic materials—among them pumice—as they may significantly reduce the environmental damage [91]. Therefore, the options with the best environmental performance in all the impact categories were the PU-WO and the PU-PV.

Given the importance of the construction industry in the use of energy [47] and GHG emissions [92], in Figure 9 these categories are dealt with separately, breaking the CED down into its proportional Renewable (Re) and Non-Renewable parts (n-Re). The percentage of CED (n-Re) for all cases is significantly higher than the CED (Re), being 84.8% for stage A, 67.6% for stage B and 98.8% for stage C of the CED total. Of the three stages, B makes greater use of renewable sources due to the use of wood in the doors and windows, followed by A, especially when the options PE-WO and PU-WO are evaluated. Some authors mention the advantages of using wood due to the low energy requirements of its manufacture [76]. Similarly, it can be seen that stage C is practically dependent on CED (n-Re), due to the machinery (C1) and vehicles (C2) used.

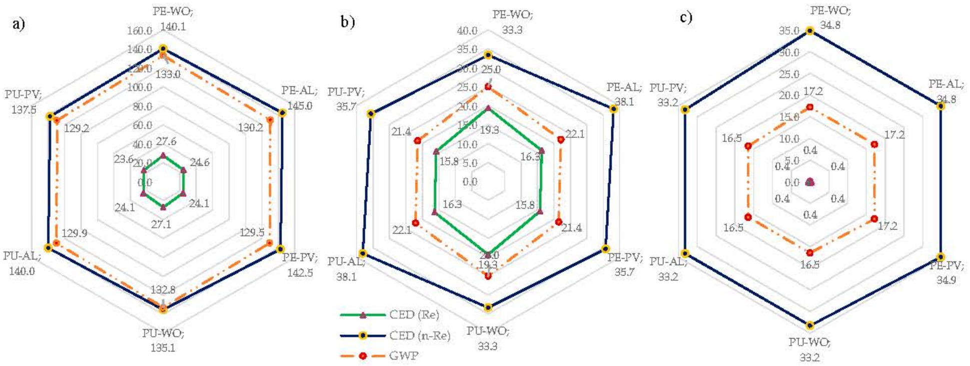

Figure 9. GWP, CED (Re), and CED (n-Re) caused at each stage of the SH: (**a**) A1 to A5, (**b**) B2, B4 and, (**c**) C1, C2, C4.

The results found for the CO_2 eq emissions and the consumption of incorporated energy are figures that are found in the list of effects reported by other researchers (Table 12). The information has been compared with that of residential, office, and commercial buildings, all of which have similar characteristics in terms of the materials used in their construction (reinforced concrete framework and traditional masonry). The majority evaluate the same components of the building (including the structure and envelope) which enables comparison. In SH the interior partitions are also evaluated.

Table 12. kg CO_2 eq and MJ eq generated by 1 m^2 of building in stages A, B and C. Data from: [48,49,78,93–95].

				kg CO_2 eq/m^2			MJ eq/m^2		
Study	**Database**	**Building Type**	**Location**	**A**	**B**	**C**	**A**	**B**	**C**
Current study	ecoinvent 3.4	Detached house	Mexico	309	54	40	3911	1251	815
Iddon et al. [93]	ICE 2.0	Detached house	UK	296	-	-	-	-	-
Islam et al. [48]	AusLCI	Attached house	Australia	257	64	-	3743	1257	-
Othman et al. [49]	Athena	Office building	U.S.	480	77	127	5597	1133	2030
Goggins et al. (floor slab) [95]	Bibliography	Office building	Ireland	211	-	-	1167	-	-
Gustavsson et al. [94]	ENSYST	Residential building	Sweden	-	-	-	3569	-	159
Sandanyake et al. [78]	AGGA/Alcorn	Commercial building	Australia	524	-	-	-	-	-

The SH analyzed emits 309 kg CO_2 eq/m^2 and needs 3911 MJ eq to perform stages A1 to A5; it also emits 54 kg CO_2 eq/m^2 and needs 1251 MJ eq for stages B2 and B4, similar to what was reported by Iddon et al. (2013) [93], Islam et al. (2015) [48] and Gustavsson et al. (2010) [94]. Additionally, when the impacts of the SH are compared with multi-story commercial or office buildings, although the results alternate within the same level of effect, the values tend to be higher in an interval of 30% to 40%. The stage showing most variation was C; as each study focused on specific end of life scenarios, their comparison was not feasible.

For stages A and B, the level of comparison is especially interesting, as each study was carried out in different geographical regions and with different databases. Therefore, it can be argued that the LCA is an objective methodology which allows global results in the residential sector to be obtained and it has been possible to standardize them, above all in the Product Stage (A1 to A3).

Considering the representativeness of the housing types in Mexico (11% economic, 47% popular, 30% traditional, 12% medium, residential, and residential plus [40], each of which was assigned 4%), it was possible to obtain an approximation of the effects of their embodied stages. One square meter of construction (A1 to A5) produces 309 kg of CO_2 eq and needs 3,911 MJ; as about 600,000 new housing units are built annually in Mexico [41], the total annual effect of the residential sector in stages A1 to A5 (until the finished house) is 11,275.8 Gg CO_2 eq and 142.5 PJ eq of energy (Table 13).

Table 13. Gg CO_2 eq and PJ eq generated annually by the construction of housing in Mexico.

Housing	Area	Gg CO_2 eq/m^2	PJ eq/m^2	Annual Housing Construction	Gg CO_2 eq/m^2	PJ eq/m^2
Economic	30.00	9284.30	117,318.50	66,000.00	612.76	7.74
Popular	42.50	13,152.75	166,201.21	282,000.00	3709.08	46.87
Traditional	62.50	19,342.28	244,413.55	180,000.00	3481.61	43.99
Medium	97.50	30,173.96	381,285.13	24,000.00	724.18	9.15
Residential	145.00	44,874.09	567,039.43	24,000.00	1076.98	13.61
Residential +	225.00	69,632.22	879,888.77	24,000.00	1671.17	21.12
Total				600,000.00	11,275.78	142.48

Additionally, using the national inventory of CO_2 eq emissions and compounds, these figures represent 2.1% of the net emissions (taking absorption into account), and 1.7% if total emissions are considered. Added to the 4% emissions from the housing sector due to consumption of natural gas, liquid petroleum gas, kerosene, diesel, and firewood in the operating stage [13], this means that 6.1% of the annual emissions may be attributed to the residential sector. Similarly, as regards the national energy inventory [14], the figures represent 2,7% of the annual consumption. This, when added to the 14% operational energy consumption, gives an estimated total of 16.7% of energy attributed to the residential sector (Table 14).

Table 14. GHGs and energy of the residential sector necessary for the construction of housing (A1 to A5) and its operational energy (B6). Data from [13,14].

Impacts of Residential Sector in Mexico (Stage)	Quantity	National Representativeness	
Emissions Gg CO_2 eq (A1 to A5)	11,275.8	2.1% [1]	1.7% [2]
Emissions Gg CO_2 eq (B6) [13]	21,279.9	4.0% [1]	3.1% [2]
Net emissions Gg CO_2 eq [13]	534,613.0		
Total emissions Gg CO_2 eq [13]	682,959.0		
Energy consumption PJ eq (A1 to A5)	142.5	2.7%	
Energy consumption PJ eq (B6) [14]	751.6	14.0%	
Total energy consumption PJ eq [14]	5362.8		

[1] Considering net emissions. [2] Considering total emissions.

Although it is evident that performance in the housing sector in Mexico is steadily improving, it is essential to deal with the accelerated changes that are being caused by environmental damage, not only at a regional level but also at a global one. The residential sector has an enormous potential to reduce these environmental burdens (including those of greatest concern today, such as climate change and the depletion of resources and non-renewable energy), throughout the various sectors that are required for its praxis. In this regard, it is necessary to opt for locally available materials, with high percentages of reuse, with thermal properties that enable energy optimization and, of course, that these should come where possible from renewable resources or from the discreet use of non-renewable resources.

On the other hand, while the importance of SH in the residential sector is indisputable, there is also a need to apply sustainability criteria to medium and residential housing. Although their representativeness is lower, in this work it was estimated that the resources invested in them (because of their size) could generate loads greater than 30% in GWP and CED, and the application of eco-technologies could be economically feasible (limitation present in the SH).

Moreover, while it is true that the LCA is a methodology that has been used in Mexico for decades [26], extending its application to one of the country's most demanding sectors would provide opportunities for reducing environmental burdens. This, through knowledge of the most commonly used materials and the processes required throughout the life cycle of a dwelling. This knowledge would enable the best environmental performance options to be chosen, and the opportunities for improvement would be identified.

5. Conclusions

The present study has assessed the environmental impacts generated by an SH throughout its embodied life cycle; a comparison of six alternatives was made by varying their elements (walls and windows), and it was possible to apply the LCA methodology to Mexico's residential sector with promising results. In addition, a review of the country's environmental situation focusing on the most relevant problems facing the residential sector was made.

It was found that throughout the cycle the SH analyzed generates an environmental burden of 17 t CO_2 eq, 252.5 GJ eq, 104.3 kg antimony eq, and 9.4 t 1.4-DCB eq; the requirements of stages A1 to A5 stand out, exceeding 70% of the impact in all the categories analyzed. In general, the stages with the greatest environmental effect are those containing a finished product (A1 to A3, B2, and B4: 78% CED-ADP; 85% GWP; 91% HTP), while the stages referring to the processes have a considerably lower impact. For A4 + C2 the figures are 3.3% HTP, 7.7% GWP, 9.3% CED, and 10.1% ADP. For A5 + C1 they are 3.7% HTP, 6.1% GWP, 7.6% ADP, and 9% CED. Finally, C4 has 1.5% GWP, 1.6% HTP, 3.7% CED, and 3.9% ADP.

The greatest variability in the results comes from changing the wood or PVC windows for aluminum windows in the HTP category, passing from 11–12% to 19% of the total damage, which is attributed to the aluminum production process.

The most unfavorable of the six cases analyzed was the reference sample (PE-AL), while the options with the best environmental performance were PU-WO and PU-PV for all impact categories. Environmental advantages can arise from using aggregates that could lighten the concrete for configuring the walls, as long as their environmental burden is equal to or less than that of conventional aggregates, and their basic attributes are not reduced.

The SH evaluated emits 309 kg CO_2 eq/m^2 in A1 to A5, 54 kg CO_2 eq/m^2 in B2 and B4, and 40 kg CO_2 eq/m^2 in C1, C2, and C4. It requires 3,911 MJ eq in A1 to A5, 1,251 MJ eq in B2 and B4, and 815 MJ eq in C1, C2, and C4. This data was collated with recent studies and, although they were carried out in different regions and developed with different databases, the results show consistency. Therefore, it was concluded that the methodology generates objective and global results in the residential sector and that, with the continuous improvement in standardization, it is increasingly possible to apply around the planet, especially in stages A1 to A3.

On the other hand, although ecoinvent regularly incorporates information from different regions of the world, it is urgent to create local databases in Latin America or in the case of Mexico expand the number of data for the existing one—mexicaniuh [96].

Considering the annual amount of the different types of dwellings built and their effect per m^2 as obtained in this study, an estimate of the annual impact of the residential sector on the finished housing (A1 to A5) was obtained. This was 11,275.8 Gg CO_2 eq, or 2.1% of net emissions. When added to the 4% emitted in the operation of the dwelling (B6) and the compound emissions, according to the national GHG inventory, this gives a total of 6.1% emissions attributed to the residential sector. Similarly, according to the national energy inventory, the estimated energy required by the residential sector in its finished housing phases (A1 to A5) is 142.5 PJ, or 2.7% of annual consumption. When added to the 14% operational energy consumption, this gives a total estimate of 16.7% of energy attributed to the residential sector.

Finally, it will be interesting in future research to obtain the CO_2 eq emissions of the residential sector and the energy eq required to carry out phases B and C annually, as well as to know the environmental impacts produced by public and commercial buildings (in addition to civil works), with the aim of obtaining the total burden generated by the construction industry in Mexico.

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Abbreviations

1,4-DCB	para-dichlorobenzene
A1 to A3	Product stage
A4 to A5	Construction process stage
ADP	Abiotic depletion potential
AL	Aluminum
B1	Use
B2	Maintenance
B3	Repair
B4	Replacement
B5	Refurbishment
C1	Deconstruction/demolition
C2	Transport
C_2F_6	Hexafluoroethane
C3	Waste processing
C4	Disposal
CDW	Construction and demolition waste
CED	Cumulative energy demand
CF_4	Tetrafluoromethane
CH_4	Methane
CO_2	Carbon dioxide
CONAVI	National Housing Commission
EPS	Expanded polystyrene
EU	European Union
Gg	Millions of tons
GHGs	Greenhouse gases
GJ	Gigajoules
GLO	Global
GWP	Global warming potential
HAP	Polycyclic Aromatic Hydrocarbons
HTP	Human toxicity potential
IPCC	Intergovernmental Panel on Climate Change
LAC	Latin America and the Caribbean
LCA	Life Cycle Assessment
MSW	Municipal solid waste
N_2O	Nitrous oxide
n-Re	Non-Renewable
PE	Hollow block of $12 \times 20 \times 40$ filled with expanded perlite
PFC	Perfluorocarbons

PJ	Petajoules
PU	Solid concrete brick lightened with pumice aggregates of $10 \times 14 \times 28$
PV	PVC
Re	Renewable
RNA	Northern America
RoW	Rest of the World
SH	Social housing
SO_2	Sulfur dioxide
tkm	ton-kilometer
U	Thermal transmittance
U.S.	United States
WO	Wood
λ	Coefficient of thermal conductivity

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CAPÍTULO 4

DISCUSIÓN GLOBAL DE LOS RESULTADOS Y CONCLUSIONES

4.1 DISCUSIÓN GLOBAL DE LOS RESULTADOS

En esta tesis se abordaron los impactos ambientales de las etapas incorporadas de elementos de la vivienda y de su entorno urbano. Se encontró que la etapa de mayor afectación ambiental es la de producto (A1-A3), es decir, la concepción del material que va desde la extracción de la materia prima hasta su producción. Cuando se estudiaron los muros exteriores el promedio de los impactos generados por la A1-A3 fue de 91%, cuando se evaluaron las calles fue desde 85% hasta 96%, y cuando se evaluaron las viviendas sociales fue de 65%. Mientras más amplios fueron los límites temporales de los sistemas, menor fue la repercusión de la A1-A3; por ejemplo, al realizar la evaluación completa del ciclo, los impactos se distribuyeron al resto de las etapas, como al mantenimiento (B2) y al reemplazo (B4).

Algunos materiales tienen potenciales de daño mayores que otros, esto se hizo evidente con el granito utilizado en las aceras del estudio de las calles, en donde los impactos ambientales ascienden desde un 85% de todo el ciclo cuando se utilizan hormigón y asfalto hasta un 96% cuando se reemplazan por granito. Esto ocurrió también con el poliestireno extruido (XPS) utilizado como aislamiento en los muros exteriores, el cual comparado con el resto de los materiales utilizados es más dañino. Por lo que, los impactos ambientales de la A1-A3 variaron en función de los límites temporales del sistema de ACV (a más etapas consideradas, menor impacto relativo) y del potencial de daño individual de los materiales implicados.

Se encontró que las etapas referentes a los procesos (trasporte, construcción, deconstrucción, entre otros) producen menores impactos ambientales que las etapas referentes a los productos, siendo el transporte la más relevante con porcentajes de daño de hasta un 15%; a continuación, las etapas de construcción y demolición con hasta un 6.6% (3% en los estudios donde sólo se consideró la construcción); y por último, la disposición final con menos del 4% (promedio de todas las categorías de impacto evaluadas).

En esta tesis se corroboró la influencia que tiene la industria de la construcción en el cambio climático. Esto porque GEI como el CO_2 y el N_2O son parte intrínseca de las reacciones que ocurren durante el proceso de manufactura de los materiales más utilizados en la construcción, como el cemento (utilizado para fabricar hormigón, mampostería, mortero, entre otros) y las piezas cerámicas de arcilla. Las altas temperaturas utilizadas en la cocción de las piezas cerámicas, hasta de 1300º [114], y en la cocción del clínker, hasta 1400º, así como el alto contenido de carbonatos encontrados en sus materias primas elementales (como la caliza y la arcilla) son responsables de la liberación de CO_2 a la atmósfera [1]. Además, la producción de gases nitrogenados es inevitable debido a las altas temperaturas alcanzada en la cocción de las piezas [115].

Considerando el peso y la proporción de los materiales que se evaluaron en esta tesis, se pueden nombrar como principales a: 1) piezas de mampostería de hormigón y piezas cerámicas de arcilla; 2) elementos de la calle de hormigón, elementos de asfalto mástico y elementos de granito; y 3) piezas de mampostería de hormigón y de hormigón aligerado con pumicita. El comportamiento ambiental de éstos varió dependiendo la categoría de impacto evaluada, por ejemplo, se encontró que:

1) Las piezas cerámicas de arcilla generan 14% más potencial de calentamiento global (PCG) que las piezas de hormigón; y que el hormigón, genera 113% más PCG que el asfalto.
2) Las piezas de hormigón generan 40% más potencial de toxicidad humana (PTH) que las piezas cerámicas de arcilla y 70% más que el asfalto. Además, 51% más daños a los efectos respiratorios.
3) El asfalto consume 121% más combustibles fósiles que el hormigón y las piezas cerámicas de arcilla contribuyen 50% más al agotamiento de los recursos abióticos (ARA) que el hormigón.
4) El granito genera en promedio 270% más daño a las áreas de protección salud humana, recursos y calidad del ecosistema que el asfalto y el hormigón.
5) Aligerar las piezas de hormigón con áridos de pumicita genera ventajas medioambientales, por ejemplo, disminución del 3% del consumo energético y del potencial de toxicidad humana en la etapa de producto; además, al ser más ligero sus ventajas se trasladan a otras etapas como el transporte y el final de la vida, mientras que sus propiedades térmicas son superiores a las de las piezas de hormigón convencional.

Además de los materiales anteriores se evaluaron otros que en peso y proporción son menores que los principales. Estos son: 1) piezas ligeras cerámicas de arcilla, placa de yeso laminado, aislamientos provenientes de hidrocarburos (XPS, poliestireno expandido (EPS), poliuretano proyectado) y de lanas naturales (lana de roca y lana de vidrio); 2) ventanas de aluminio, ventanas de PVC y ventanas de madera. De estos materiales se encontró que:

1) Los muros elaborados con placa de yeso laminado contribuyen más al PTH, al potencial de acidificación (PA) y al potencial de eutrofización (PE) que los muros elaborados con piezas cerámicas de arcilla (2.5, 5.3 y 3.7, veces respectivamente, éstos valores se deben en un 80% al galvanizado del perfil de acero).
2) Los aislamientos térmicos elaborados con hidrocarburos generan más PCG, ARA y PA que los elaborados con lanas naturales (2.3, 3, 1.15, veces respectivamente); mientras que las lanas naturales generan 3.4 más PTH.
3) Al evaluar las viviendas sociales, la mayor variabilidad se dio para el PTH cuando se cambiaron las ventanas de madera o PVC, por ventanas de aluminio, pasando de un 12% a un 19% del daño total de la vivienda.
4) Las ventanas de aluminio son: 2.8 y 2.1 veces más generadoras de PCG y, 6.6 y 4.7 veces más de PTH. Son 2.5 y 1.4 veces más consumidoras de energía no renovable y, 2.7 y 1.7 veces más de recursos abióticos que las ventanas de madera y de PVC, respectivamente.

Por lo tanto, los impactos ambientales de la A1-A3 tienen que ver en primer plano con la naturaleza del material utilizado y en segundo, con las dimensiones del elemento. Por ejemplo, el uso de piezas de gran formato, en especial las piezas machihembradas, reduce el mortero utilizado en la conformación de los muros, lo que reduce los impactos ambientales; o el incremento controlado del espesor del aislamiento térmico. Ambas medidas son estrategias simples que permiten el control de los impactos finales.

Los resultados anteriores se refieren a la comparación de las afectaciones que generan los elementos en conjunto, es decir, a las cantidades equivalentes que se requieren para cada caso particular de cada artículo y no se deben a la afectación con respecto a cada kilogramo de material utilizado. Para este último fin, en el primer artículo se propuso un sistema de ecuaciones que permitió predecir el comportamiento ambiental que producen los muros exteriores o cualquier elemento diseñado con éstos materiales.

El sistema de ecuaciones además de ser una herramienta útil para los responsables de la construcción en la búsqueda de opciones ambientales amigables, proporciona la variación con la que aumenta el daño ambiental entre kilógramo de material utilizado. Las gráficas de los aislamientos térmicos son las que presentaron la mayor pendiente en todas las categorías de impacto (mayor carga ambiental), para el resto de los materiales dependerá de la categoría de impacto evaluada (este resultado se puede consultar en el artículo 1, capítulo 6).

A pesar de que la A1-A3 es la que mayor afectación genera en todas las categorías de impacto analizadas, el resto de las etapas tienen la capacidad de aligerar las cargas ambientales, ya que la mayoría de éstas suceden en lapsos reducidos de tiempo y dependen de acciones más simples que la complejidad que comprende la etapa de producto. En este sentido, este análisis subrayó la importancia de considerar al transporte.

En el primer artículo se realizó un análisis de sensibilidad y se detectó que el transporte era la etapa que presentaba mayor grado de incertidumbre. Se realizaron doce combinaciones de estudio donde se variaron las ubicaciones de las plantas de producción y los rendimientos ecológicos de los camiones utilizados para el transporte de los materiales a los sitios de construcción. El análisis destaca la relevancia de considerar esta etapa en el ACV, ya que los diferentes escenarios propuestos muestran importantes variaciones, lo que puede significar aumentos de hasta un 42% y reducciones de hasta un 8% en los impactos ambientales producidos durante las etapas de la cuna a la entrega (A1–A5). El ARA y PA son las categorías más sensibles.

Además de destacar la etapa de transporte, en esta tesis se evidenció la importancia de considerar las etapas del uso, por ejemplo, el mantenimiento y el reemplazo en conjunto generan impactos que van desde el 13% hasta el 21% de todo el ciclo de vida dependiendo de la categoría de impacto evaluada. Éstas tienen intrínsecas etapas de sus propios productos, por ejemplo, las ventanas, las puertas, la pintura del mantenimiento, entre otros elementos o actividades que se requieren atender más de una vez en la vida de un edificio.

Por otra parte, al evaluar el entorno urbano se encontró que dar prioridad a la escala humana promoviendo el flujo de tráfico no motorizado cuando se configura una calle residencial, puede conducir a una reducción en el impacto generado en el medio ambiente. La configuración de la calle deberá realizarse de forma cautelosa sin olvidar la importancia que tiene la selección de los materiales, puesto que las tasas de contaminantes del granito son muy elevadas comparadas con materiales como el hormigón y el asfalto.

El comparar los impactos ambientales incorporados que genera una calle diseñada para la escala humana con respecto a la calle que prioriza el flujo motorizado, refuerza la iniciativa de diseñar calles enfocadas a crear un ambiente peatonal por las ventajas que se pueden generar en la etapa de uso. Cuando se aumentan los espacios para el flujo no motorizado, la reducción en los impactos ambientales puede ir desde un 11.5% hasta un 22.3% para las configuraciones de calles analizadas en el artículo dos, siempre que se utilicen materiales convencionales como el hormigón o el asfalto.

Por otra parte, se encontró el desempeño ambiental de una vivienda social para cuatro categorías de impacto evaluadas. Si bien será necesario en un futuro evaluar nuevas y diferentes tipologías de vivienda social para poder que este estudio sea comparable y concluyente, los resultados que se obtuvieron son un inicio prometedor sobre la aplicación de la herramienta ACV en la construcción del ámbito mexicano.

Los resultados de energía y emisiones incorporadas fueron cotejados con información de estudios realizados en edificios (entre ellos de vivienda). Se encontró que la vivienda evaluada emite alrededor de 309 kg CO_2 eq/m^2 y que las viviendas con las que se comparó oscilan en estos valores. Los edificios de varios niveles destinados a otros usos, como comercial y de oficinas, presentaron valores mayores en un intervalo del 30 al 40%. Por lo que se considera que los datos obtenidos mostraron congruencia con la bibliografía ya publicada. La etapa que no fue posible comparar fue la del final de la vida, dada la notable diferencia que se tiene con otros países respecto a la gestión de residuos y de disposición final.

Después de haber obtenido los datos sobre energía y emisiones de la vivienda social por m^2 y considerando la cantidad anual de los diferentes tipos de viviendas construidas, se obtuvo una estimación del impacto incorporado anual que produce el sector residencial (sólo hasta la vivienda terminada, es decir A1-A5). Se encontró que la construcción anual de las viviendas en México equivale al 2.1% de las emisiones netas del país, que sumado al 4% de la operación de los hogares (dato del inventario nacional), suma un 6.1% imputable al sector residencial. Se realizó el mismo procedimiento con el consumo de energía, la construcción de vivienda equivale al 2.7% anual del consumo total del país, que sumado al 14% de su operación (dato del inventario nacional), suma un 16.7% imputable al sector residencial. A estas cifras será necesario incluirle los impactos correspondientes de la etapa de uso (B1-B5) y de final de la vida.

Los anteriores son algunos de los resultados más relevantes obtenidos en esta tesis. Parte de éstos son comunes debido a la utilización de la misma metodología y parámetros, mientras que otros son específicos de cada artículo. Para mayor información sobre resultados particulares, se recomienda revisar el capítulo 3, donde se expone cada uno de los artículos.

4.2 CONCLUSIONES

En esta tesis se corroboró que el ACV es una herramienta aplicable a la construcción, tanto al ámbito de la edificación, como del urbanismo. Pone de manifiesto que es una metodología flexible que permite utilizar diferentes recursos adaptados a las peculiaridades de cada análisis. Aún con esta flexibilidad se considera que los resultados son confiables y replicables no sólo en una región geográfica, sino en el mundo.

Asimismo, con la implementación y la actualización de la normativa, la metodología se estandariza día con día; la ejecución de estudios que comparten similitudes al basarse en normativas equivalentes (tanto las europeas, como las internacionales) deriva en estudios comparables con resultados cada vez más globales. Sobre todo, esta estandarización se logra en la etapa de producto, la cual generó la menor variación tanto en este estudio, como en los estudios que sirvieron de marco teórico.

La evolución de la metodología en el sector de la construcción desde 2015 que se inició esta investigación hasta el presente año ha sido progresiva, ya que los parámetros que representaban limitaciones, como la terminología, la escala temporal del sistema y los datos del inventario de ciclo de vida, ahora muestran más transparencia, claridad y se expanden a nuevas geografías. Permitiéndole ser una metodología no sólo de países desarrollados, sino que su campo de aplicación es factible (y además recomendado) en países emergentes y en países en vías de desarrollo. El ACV tiene un potencial de contribución de esquemas de evolución sostenible.

Por otro lado, el realizar ACV parciales o con enfoques que abarquen sólo una línea del tiempo permite concluir resultados más particulares, por ejemplo, qué materiales son más convenientes, conocer a detalle la sensibilidad de alguna etapa (y como oscilará en dependencia de las variables que se establezcan), proponer mayor número de escenarios, entre otros. Por su parte, evaluar todo el ciclo de vida de un producto o proceso genera ventajas obvias, como evitar transportar cargas no deseadas a otras etapas del ciclo de vida, conocer la implicación real de un producto o proceso a lo largo de su ciclo de vida, conocer en qué parte del ciclo de vida será conveniente la aplicación de estrategias, esfuerzos y recursos para obtener mejores resultados.

Lo anterior se evidenció con ambos enfoques que se utilizaron en esta tesis, por ejemplo, al evaluar sólo los límites de la cuna a la entrega fue posible establecer un mayor número de escenarios y compararlos hasta encontrar la alternativa correcta para el medioambiente; mientras que, al evaluar la línea de la cuna a la tumba, los escenarios tuvieron que ser limitados debido a la complejidad del estudio, sin embargo los resultados fueron del ciclo completo, lo que permitió detectar las oportunidades de mejora. Por lo que se recomienda la realización de ACV completos, y posteriormente, ACV parciales en las áreas de detección de mejora.

La comparabilidad de los resultados obtenidos en el artículo tres, con investigaciones previas (comparación de la vivienda social con edificios residenciales, comerciales y de oficinas) tuvo peculiaridades destacables, debido a que los estudios de comparación fueron realizados con bases de ICV distintas a ecoinvent y fueron llevados a cabo en diferentes regiones geográficas, teniendo en común los elementos analizados (marco de hormigón reforzado y muros de mampostería).

En los tres artículos presentados se puso de manifiesto que una de las limitaciones del ACV con el tiempo se ha ido superando (es decir, la falta de comparabilidad por causa del ICV) debido al importante número de investigaciones que se han realizado y, sobre todo, debido a la estandarización exhaustiva de la metodología. Para el caso específico de México, a pesar de que ecoinvent ha incorporado datos de países diferentes a Europa (como países de ALC) sigue siendo necesario realizar análisis con datos propios del proceso, en especial para aquellos casos de materiales específicos (como nuevos materiales) o aquellos en donde los procesos sean dependientes de la región donde se estén utilizando.

Los ACV realizados permitieron conocer las cargas ambientales de algunos de los materiales más utilizados en construcción e identificar aquellos que tuvieron los potenciales de daño más elevados, así como proponer estrategias para limitar estas cargas. A partir de los resultados se pudieron establecer ecuaciones de regresión lineal del comportamiento ambiental de cada material y realizar combinaciones adecuadas en la configuración de elementos residenciales, en este caso específico, de los muros de la envolvente. Además, el análisis de sensibilidad realizado permitió identificar las zonas que mayor variabilidad tuvieron en el estudio.

En esta tesis se exhibieron las ventajas que tiene el priorizar la escala humana en el diseño urbano, no sólo por los beneficios que ya se han establecido en investigaciones previas referentes a las etapas de su uso, sino también desde el punto de vista de su construcción. La variación en las dimensiones de las calles, las aceras y las áreas verdes influye en los impactos ambientales totales, los cuales se pueden intensificar si además se utilizan materiales con cargas ambientales elevadas.

Por otro lado, si bien la importancia de la vivienda social en el sector residencial es indiscutible en países como México, es necesario aplicar de igual forma criterios de sostenibilidad a viviendas medianas y residenciales. Aunque su representatividad en el parque habitacional nacional es menor, en este trabajo se estimó que los recursos invertidos en éstas podrían generar cargas superiores al 30% en el potencial de calentamiento global y en la energía incorporada. Además, en estas tipologías de vivienda, la aplicación de ecotecnologías es económicamente factible (limitación presente en la vivienda social).

Por lo encontrado en estos tres artículos, se recomienda optar por materiales con disponibilidad local, con altos porcentajes de reutilización, con propiedades térmicas que permitan la optimización energética y, por supuesto, que estas tengan como origen (en la medida de lo posible) a fuentes renovables o que utilicen a discreción los recursos no renovables.

Estas conclusiones son algunas de las particularidades que se obtuvieron con el ACV, las cuales fueron dependientes de las categorías de impacto que se analizaron o de los métodos de impacto ambiental seleccionados, así como de la base de datos que se utilizó. En esta tesis, el ACV se pudo aplicar tanto a la edificación, como al urbanismo, arrojando resultados satisfactorios con potencial de mejora en los rubros que se evaluaron. Permitió proponer y establecer estrategias para que los responsables de la construcción apliquen de una forma más simple el pensamiento de ciclo de vida. Aportó información relevante y una línea de investigación potencialmente fructífera para la continuación del estudio.

Esta tesis puso de manifiesto que el ACV es una herramienta que puede contribuir a la obtención de los objetivos del desarrollo sostenible de la Agenda 2030 y que es esencial para hacer frente a los cambios acelerados causados por el daño ambiental, no solo a nivel regional sino también a nivel mundial. Los sectores residencial y urbano tienen un enorme potencial para reducir las cargas ambientales que mayor preocupación causan en la actualidad (como son el cambio climático y el agotamiento de los recursos y la energía no renovable) y que son inherentes a todos los sectores que se requieren para la praxis de la construcción.

4.3 INVESTIGACIÓN A FUTURO

Después de analizar elementos de edificación y urbanismo se espera que el trabajo de esta tesis se continúe desarrollado. Por ejemplo, se pretende evaluar en trabajos futuros la influencia de las propiedades de los materiales en la reducción de las cargas ambientales durante la vida de los elementos urbanos considerando aspectos como la isla de calor, la demanda energética de los entornos urbanos y la durabilidad de los materiales utilizados, es decir su etapa de uso. Además, evaluar la influencia que tienen algunas condiciones especiales, como la radiactividad del granito en la salud humana o la posible variación que la reducción del flujo motorizado ejercerá en parámetros como el aumento del tráfico por la modificación de la velocidad y de los carriles destinados para el uso del automóvil. Estos aspectos permitirían obtener argumentos más globales sobre las ventajas de aumentar la peatonalidad de las calles.

Por otra parte, respecto al estudio de la vivienda social en México es necesario estudiar un mayor número de casos prácticos de la vivienda social para obtener resultados comparables y concluyentes; donde se incluyan nuevas geografías nacionales, así como incorporar nuevos materiales a estos estudios. Además, debido a la extensa área territorial del país, el transporte y la distribución de las fábricas son un tema que se debe abordar con detalle. Así como también, se requiere un estudio exhaustivo de la etapa del final de la vida, por las ventajas que podrían generar las posibles gestiones de los residuos y, sobre todo, de la infraestructura que existe para su disposición final.

Por otra parte, será interesante evaluar la etapa de energía y agua de operación, así como proponer mayores escenarios de la etapa de uso del edificio para complementar los ya obtenidos resultados de este estudio. Incorporar ecotecnologías y analizar la variabilidad que generan en la operación, así como la influencia que tendrán los materiales con los que se proyecta la vivienda en las etapas de operación y del final de la vida. Con estos datos sería posible establecer los impactos que genera una vivienda durante todo su ciclo de vida.

Además de la vivienda social, es necesario incursionar en el estudio de la vivienda media y residencial; incluso incorporar nuevas herramientas de análisis que complementen el ACV, como ACCV, el ACV-S, los sistemas de evaluación de la sostenibilidad, entre otros. Por último, es imperioso conocer los impactos ambientales producidos no sólo por el sector residencial, sino también por los edificios públicos y comerciales (además de obra urbana y civil) con el objetivo de obtener la carga total generada por la industria de la construcción en México.

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