Original Paper

Indoor and Built Environment

Indoor and Built Environment
2023, Vol. 32(6) 1213–1230

DOI: 10.1177/1420326X231155146
journals.sagepub.com/home/ibe
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Life cycle analysis methodology for heating, ventilation and air conditioning ductwork in healthcare buildings

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Abstract

The design, modelling and construction of heating, ventilation and air conditioning (HVAC) facilities in healthcare buildings must aim for the users' maximum comfort and meet sanitary criteria for indoor air quality. The environmental impact of 12 HVAC duct types was subjected to life cycle assessment, with a single-score damage category analysis carried out for the midpoint and endpoint levels. The two most favourable duct types for the different impact categories were aluminium with helical steel wire reinforcement and fibreglass insulation, and also copper sheeting with rock wool and polyurethane insulation. However, although the former presented the best environmental impact values, this type is inadvisable for healthcare buildings. This is due to its nature and the subsequent tendency of the system to lose pressure and efficiency, as well as the difficulty of cleaning this type of ductwork and its predisposition to bacterial proliferation. Thus, the copper duct type with rock wool insulation is the most suitable type for healthcare buildings. This came second overall environmentally (1.06 pt/m^2), with values 2.83 times more favourable than the polyisocyanurate solution. Finally, the application of the life cycle assessment (LCA) methodology to HVAC ductwork was demonstrated to reduce the impact by up to 39.88%.

Keywords

life cycle assessment, heating, ventilation and air conditioning ductwork, healthcare buildings, building projects

Introduction

The design, modelling and construction of heating, ventilation and air-conditioning (HVAC) facilities must aim for the users' maximum comfort and meet sanitary criteria for indoor air quality.[1] Thermal comfort is defined as 'the condition of mind that expresses satisfaction with the thermal environment',[2] and its evaluation is based on the guidelines of the UNE-ISO 7730: 2006 norm.[3] Besides, it is regarded as one of the main variables when considering the indoor air quality (IAQ) in a room.[4] IAQ is increasingly important as users of heating, ventilation and air conditioning systems (HVAC) spend a large part of their day indoors, constantly exposed to these environments. Loaded environments could therefore be harmful to their health.[5,6]

HVAC systems play a key role to achieve favourable air quality parameters and occupants' comfort.[7] One of the main objectives of HVAC systems is to eliminate air pollutants and concentration dilution to acceptable rates.[8] Moreover, air quality and its subsequent thermal comfort are directly proportional to the HVAC energy consumption.[9]

When designing air conditioning systems, one of the most important parts is the ductwork, as this is the physical

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medium through which the entire volume of air necessary to ventilate or air-condition a room flows.[10] Nowadays, the Spanish Technical Association for Air-Conditioning and Refrigeration (ATECYR), the Federation of European Heating, Ventilation and Air-Conditioning Associations (REHVA) and the American Society of Heating, Refrigeration and Air-Conditioning Engineers define three types of air ductwork based on the manufacturing materials: metal sheeting, non-metallics and flexible,[11–13] with the first being the most commonly used.[14] Each of these materials has different advantages and disadvantages in terms of energy efficiency, costs, thickness, noise, particulate concentration, etc. They also present different environmental impacts. Regardless of the duct type, most of the energy consumed by the HVAC system is lost in the heat transfer through the duct's contact surfaces.[15] Thus, efficiency decrease and system capacity are diminished. Losses ranged between 6% and 18% of the energy demands. These losses can be reduced by employing insulation materials and adequately controlling the air renovation rates.[16] New designs, materials and coatings have therefore been developed for air distribution ducts to reduce energy consumption. Furthermore, optimal conditions for thermal comfort were achieved.[17]

HVAC ductwork in healthcare buildings

HVAC ducts in healthcare buildings bear features and unique needs concerning the rest of the buildings. Therefore, in the rooms of hospital buildings, the choice of air distribution system is even more important as it must avoid the spread of bacteria, viruses and diseases.[18] It has been shown for example that indoor air quality in an operating room is directly related to the risk of nosocomial infection and that there is a correlation between the HVAC systems and the degree of contamination of surgical wounds.[19] Thus, in high-performance hospitals, operating rooms have appropriate HVAC systems.[20]

On the other hand, HVAC ducts used must ensure adequate air flow reception and avoid noise transmission.[21] Numerous studies show the necessity of laminar continuous air flows which may create flow patterns to displace polluted air far from the operating table and tools.[22] Besides, it is essential to design robust and accessible HVAC facilities. Thus, the probability of air escapes and degradation can be reduced.[23] Lastly, these systems must provide comfortable environmental conditions to both surgical equipment and patients parameters such as temperature, moisture and ventilation must be controlled.[24]

Background

Through the last decade, several authors had researched on enhanced insulating materials which allowed to reduce costs and improve HVAC energy efficiency. In this sense, authors like Yildiz and Ersöz[25] evaluated the thickness and performance of different insulating materials of HVAC ducts (fibreglass and rock wool). The purpose was to establish optimal thicknesses and materials at an economic scale and energy efficiency. They demonstrated that absolute improvement margins ranged from 79.36% to 98.45% depending on the material and thickness of the insulation. In line with this research, Ucar[26] analyzed other types of insulation materials (fibreglass and EPS) and added new variables such as exergy losses. A linear correlation between energy and economical savings was determined concerning the duct diameter increase. Furthermore, it was proved that the optimal insulating thickness depended on the convection heat transfer coefficient of the outer duct surface. However, there are no precedents in works which included environmental factors in design and calculation processes.

Currently, there is a general social concern about the effects of projects and human constructions on the environment.[27] Such effects may impact either positively or negatively on the environment, and they have inherent consequences. For this reason, to achieve sustainability, the environmental dimension must be incorporated into the choice of HVAC materials and systems.[28,29] Life cycle analysis (LCA) is a quantitative method of assessing the environmental impact on human health during the lifetime of a product, process or system by taking into account the extraction and processing of raw materials, their manufacturing, distribution, use, maintenance and repair, and final disposal.[30] Navigating this dimension, Shah et al.[31] were pioneer authors in carrying out a LCA of the HVAC systems of four residential buildings which had galvanized steel ducts with 50 mm fibreglass insulation. Using the Impact 2002+ method,[32] they found the greatest impacts in the human health category for the boiler and AC system (1.1 pt). In their study, the impact generated by the HVAC ducts was taken into account, but its contribution to the total impact of the system was not analyzed. This fact limits the identification and quantification of HVAC ducts impacts. Besides, comparison options between similar studies are also trimmed. Regarding the assessment of HVAC system maintenance from the environmental perspective, authors like Blom et al.[33] used the LCA method to quantitatively assess the environmental performance associated with five types of HVAC facilities. Applying the CML 2000 method,[34] they found the greatest environmental impacts (260 pt) in the human toxicity category for the electrical consumption of the HVAC system. Nevertheless, the contribution of the ducts to the total impact of the HVAC system was not taken into account. Finally, Gomes et al.[35] used the BIM-LCA method to model a building's HVAC system. Nonetheless, this methodological approach applies few impact categories and is mostly aimed at accounting for

CO_2 emissions.[36] This fact limits the LCA, so it is convenient to use traditional LCA methods that cover more varied impact categories.[37]

In the HVAC duct manufacturing field, Herranz-García et al.[38] carried out an environmental statement on fibreglass panels used in the construction of air-conditioning ducts. Using the TEAM TM 5.2 software package,[39] they demonstrated that the highest environmental impact coming from this type of duct is during the production stage. As a result, these authors obtained values up to 5.13 times higher than the next least favourable stage (construction) in the most harmful category (net freshwater use/air pollution). However, as no LCA was considered, most impact categories were disregarded, and protection areas were not quantified. In this field, Yin et al.[40] assessed the energy impact and LCC of two duct designs (flexible and metallic) for residential HVAC systems. They discovered that suitable ductwork design and modelling allowed savings of 11% and 17% for the flexible and metallic ducts, respectively. This study took into account neither the environmental impact associated with the ducts nor their installation cost. Therefore, the comparison with similar studies is unavailable, and the scope is subsequently limited.

In the line of energy efficiency, authors like Kumar et al.[41] estimated the life cycle cost (LCC) of five HVAC ductwork insulation solutions with the aim of obtaining the economically optimal insulation thickness and a new environmental variable. They concluded that insulation thicknesses between 37 mm and 51 mm were the most favourable for increasing energy efficiency and reducing environmental impact.

Finally, in the healthcare field, there are several studies which performed an environmental analysis of healthcare buildings. For example, García-Sanz-Calcedo et al.[42] identified and quantified the embodied energy in healthcare centre construction. Li et al.[43] demonstrated that hospital buildings have a greater environmental impact than residential, commercial and educational buildings. Other authors explored the environmental impact derived from different elements of the healthcare infrastructure. For example, Botejara et al.[44] evaluated the environmental impact of multiple flat roofs in healthcare buildings. In this study, the importance of including the environmental dimension in the decision-making process when selecting the flat roof was demonstrated. Nonetheless, there is no precedent of any study introducing sustainability criteria into the optimal selection of ductwork for the HVAC systems of healthcare buildings using the LCA method.

Novelty and objectives of the research

Up to now, HVAC ducts in healthcare buildings have always been sized to minimize the costs of execution and operation, without taking into account the environmental dimension. The novelty of this research focuses on the multivariable analysis of the environmental impact associated with the life cycle of HVAC ductwork and its impact on human health, resource availability and ecosystem quality. Consequently, the results of this research will generate knowledge that does not exist in the scientific literature. This will reduce the environmental impact associated with HVAC systems and, by extension, the overall healthcare infrastructure.

The main objective of the present research was to evaluate the commonest types of HVAC ductwork used in healthcare buildings using LCA. Therefore, the most suitable construction solutions were identified according to environmental impact variables, execution cost and execution time. In this way, the environmental dimension can be added to the decision-making process of healthcare infrastructure managers, combining with economic and technical factors, and optimizing their selection.

Material and methods

General method

A comparative study of different types of HVAC ducts commonly used in healthcare buildings was carried out, based on their environmental impact, according to the principles described in the ISO 14040 and ISO 14044 standards.[45,46] Figure 1 presents the LCA framework adopted in this research, which is based on the normative framework described above.

The LCA framework illustrated in Figure 1 is internationally recognized as the only framework currently supported by the scientific community for carrying out life cycle analysis.[47] The workflow for this research was planned and designed based on the framework in Figure 1. This workflow is represented in Figure 2.

First, in accordance with the LCA method, the 12 most representative types of HVAC ducts in Spain's healthcare infrastructure were defined (Table 1). This method requires the prior definition of some characteristics such as the functional unit, the scope of the study and the life cycle inventory.[48] Therefore, the next step was the definition of the functional unit. Thus, the functional unit chosen was 1 m^2 of ductwork inner surface area. Then, the scope of the study (system limit) was defined in terms of life cycle stages. For this purpose, the 'cradle to grave' approach, a principle based on the linear economic model of product use, was chosen.[49] This approach covered the extraction of raw materials, their manufacture to create the duct and its transport to the healthcare building, commissioning, useful life (25 years) and decommissioning (demolition/dismantling). Finally, the life cycle inventory (LCI) was defined for the different solutions to be analyzed (Table 1).

Subsequently, a life cycle impact assessment (LCIA) was carried out. To this end, the ReCiPe 2016 method was applied

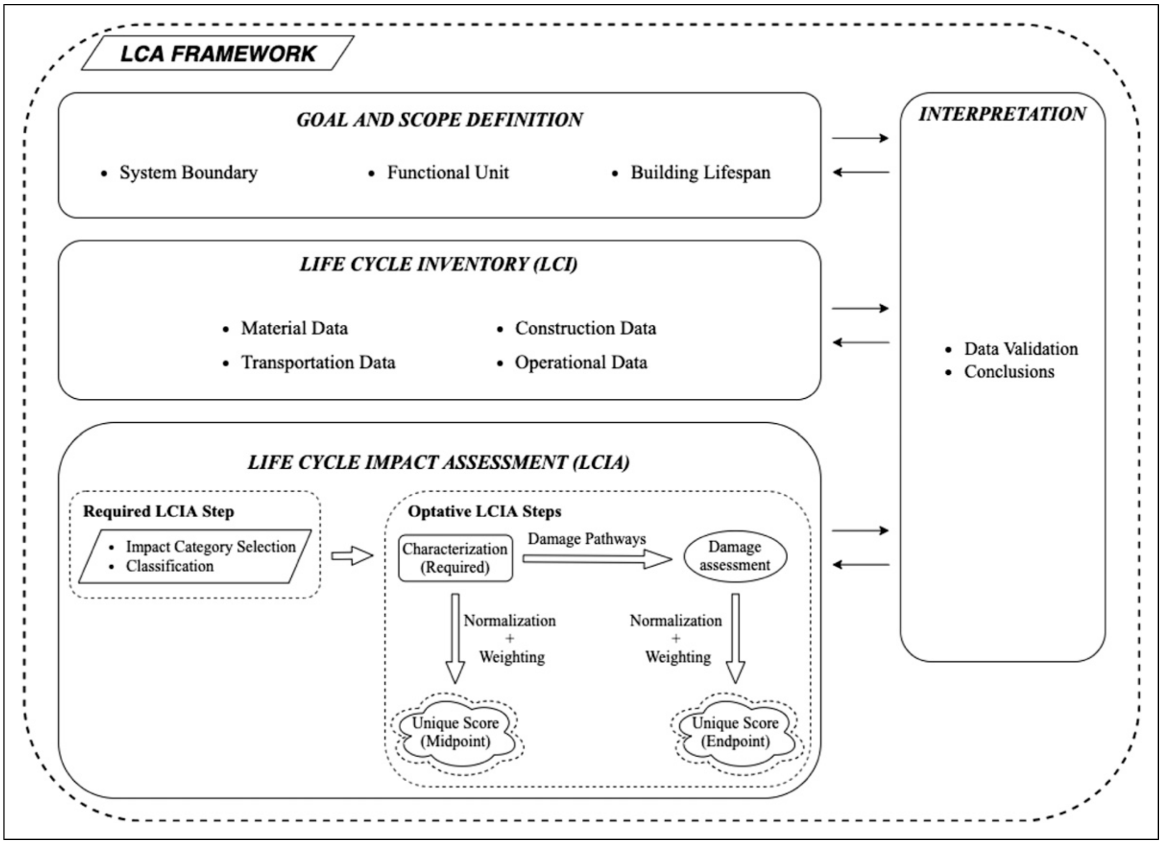


Figure 1. *Life Cycle Analysis Framework. Adapted from Refs. 45, 46.*

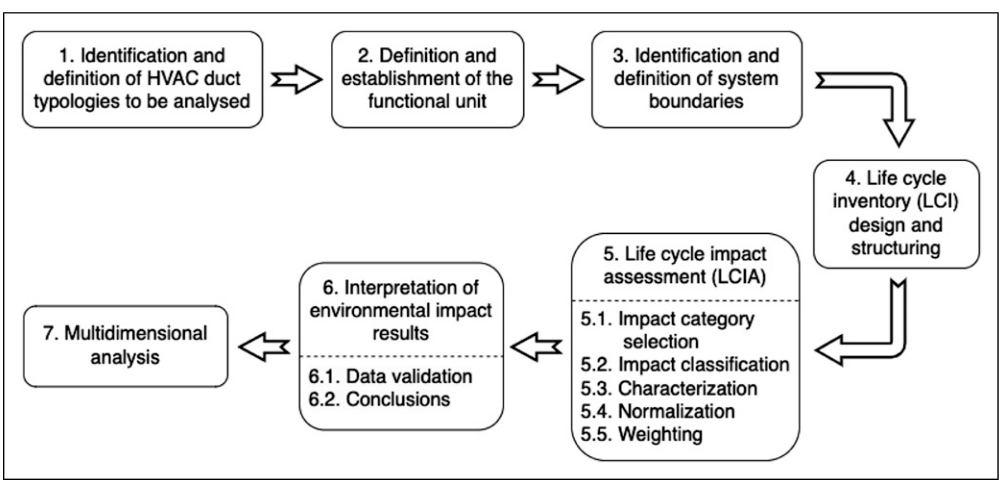
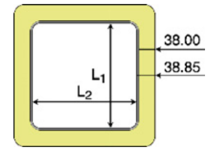
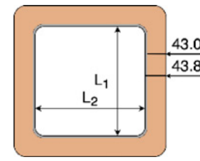
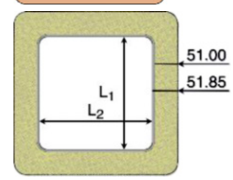
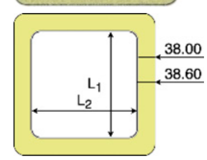
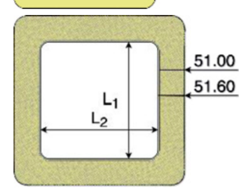
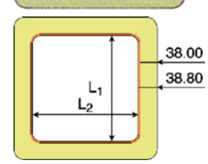
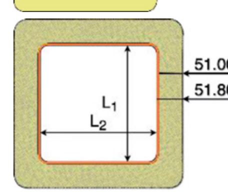
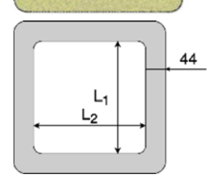
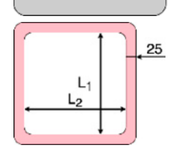


Figure 2. Research workflow.

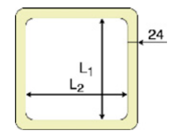
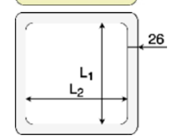
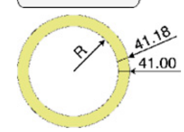
to characterize the environmental impact over the life cycle, since this method is representative at a global scale. This method of environmental assessment is one of the most representative at an international level, being one of the most commonly used methods by the scientific community.[50] In addition, several impact categories and classification processes are predefined, so the achievement of these steps of the LCA framework was automatic.[51] The simulation of the different typologies and the quantification of the impact associated with each one was carried out using the SimaPro

Table 1. Description of the proposed ductworks analyzed.

Case	Type	Description of layers	Density (ρ) (kg/ m^3)	Thermal conductivity (W/mK)	Amount (kg)	Constructive detail
#1	Sheet metal (EN 1507: 2006)	Galvanized steel sheet Fibreglass	7850 38	58 0.032	6.673 0.912	
#2	Sheet metal (EN 1507: 2006)	Galvanized steel sheet Expanded polystyrene	7850 30	58 0.036	6.673 1.283	
#3	Sheet metal (EN 1507: 2006)	Galvanized steel sheet Rock wool	7850 100	58 0.043	6.673 5.110	
#4	Sheet metal (EN 1507: 2006)	Stainless steel sheet Fibreglass	7960 38	47 0.032	4.800 0.912	
#5	Sheet metal (EN 1507: 2006)	Stainless steel sheet Rock wool	7960 100	47 0.043	4.800 5.110	
#6	Sheet metal (EN 1507: 2006)	Copper sheet Fibreglass	8960 38	385 0.032	7.168 0.912	
#7	Sheet metal (EN 1507: 2006)	Copper sheet Rock wool	8960 100	385 0.043	7.168 5.11	
#8	Non-metallic (EN 13403: 2003)	Fibreglass reinforced plastic	30	0.037	1.319	
#9	Non-metallic (EN 13403: 2003)	Phenolic foam	60	0.021	1.497	

(continued)

Table 1. (continued)

Case	Type	Description of layers	Density (ρ) (kg/m^3)	Thermal conductivity (W/mK)	Amount (kg)	Constructive detail
#10	Non-metallic (EN 13403: 2003)	Polyurethane	53	0.020	1.259	
#11	Non-metallic (EN 13403: 2003)	Polyisocyanurate	55	0.022	1.437	
#12	Flexible ductwork (EN 13180: 2001)	Aluminium with steel wire helical frame	8000	205	0.720	
		Fibreglass	38	0.034	0.727	
		Aluminium with steel wire helical frame	8000	205	0.720	

*(measurements expressed in mm).
**$L_1 = L_2$ = 250 mm (characteristic dimensions for 1 m^2 of ductwork inner surface area).
***R = 141 mm (characteristic dimension for 1 m^2 of ductwork inner surface area).

v9.0 software package.[52] The variables of the life cycle inventory (type of material, density, thermal conductivity, insulation thickness and quantity of material) and those referring to transport (type of transport and transport distance) and energy consumption (type of consumption and quantity consumed) were introduced for this purpose. Furthermore, the egalitarian perspective (E) was selected to consider the infinite time frame using the most pessimistic method.[53]

The optional steps of the LCA framework were consequently carried out. For this, doubly weighted (midpoint and endpoint) indicators were selected to classify the results by damage pathway, and to examine the individual contribution to the impact in each protected area.[54] The processes of characterization, normalization and weighting of the ReCiPe 2016 method's own results in each of the method's indicators (midpoint and endpoint) were also implemented.[55]

Finally, the process of interpretation of the results was carried out to quantify the characteristic environmental impacts of each of the HVAC duct types. In addition, as an own contribution and to complement the environmental impact analysis, other key dimensions (installation time and cost) were incorporated into the process of deciding on the most favourable type of duct. From the unit price and labour performance, the cost and material execution time were obtained for the functional unit of each type of duct. The unit price and labour performance values were calculated from specialized construction databases.[56] To this end, the prices and installation times of the different LCI materials were identified and grouped for each HVAC duct typology based on the functional unit 1 m^2 of ductwork inner surface area. This provided a complete analysis of the optimal solution for healthcare buildings.

Case descriptions

The different HVAC duct typologies were identified by analyzing 34 healthcare buildings in different healthcare areas in Spain. Subsequently, a comparative LCA was carried out for the 12 commonly used HVAC duct types, checking firstly that they met the minimum requirements established in terms of health requirements and their respective technical characteristics. The following working conditions were established: outdoor temperature of 10°C, indoor temperature of 25°C and air-flow speed of 4 m/s.[57]

The ducts selected have two types of geometric cross-sections, one rectangular and the other circular depending on the type of duct. In particular, it was rectangular for the metallic and non-metallic sheet ducts, and circular for the flexible ducts.

On the other hand, the thickness of the materials depended on the nature of each duct. This was mainly due to the fact that each material has a different thermal conductivity (λ). To calculate the thickness of each proposal, Aislam v1.0 software package was used,[58] which was based on equation (1)[57]

$$t = 30\left(\frac{\lambda}{0.025}\right) \tag{1}$$

where t is the insulation thickness and λ is the thermal conductivity expressed in W/(mK). Table 1 lists the main characteristics of the different duct proposals.

Life cycle inventory

A life cycle inventory (LCI) was made of the materials necessary for the construction of a functional unit of each type of duct, using for this purpose the database provided by Ecoinvent 3.5.[59] This LCI is listed in Table 1.

Table 2 shows the average transport distance (T_d) from the factories to the healthcare buildings for each of the materials that compose the different types of ducts. In this way, a single distance per material was considered for the set of 34 healthcare buildings under study. Thus, a standardization of the LCA process was achieved with reliable results that can be extrapolated between healthcare buildings. Furthermore, EURO4 trucks were defined as the materials transport medium.

Table 2. Average transport distances factory-healthcare building for the different materials analyzed.

Materials	T_d (km)	σ_d (km)
Galvanized steel	180	±55.93
Fibreglass	360	±78.43
Expanded polystyrene	360	±72.67
Rock wool	360	±67.88
Stainless steel	180	±49.34
Copper	180	±57.13
Fibreglass reinforced plastic	360	±85.51
Phenolic foam	360	±107.73
Polyurethane	360	±69.06
Polyisocyanurate	360	±117.24
Aluminium	180	±55.82

Finally, at the end of the ducts' useful life, it was estimated that machines would be used to dismantle them and transport them 25 km to a waste management point using a 16–32 ton EURO4 type truck.

Results

LCA results

Figure 3 shows the first result obtained from the life cycle analysis process using SimaPro v9.0 software, called characterization of the impact categories. This quantification establishes three categorical groups based on the scale of measurement (€, DALY and species·yr) and is essential to understand the damage flow followed in subsequent stages of the LCA. Thus, for this first approximation, the least favourable impact category of the DALY score was that of non-carcinogenic human toxicity (HnCT), in which duct types #9 and #11 stand out, with #11 being the one with the greatest impact ($4.5{\cdot}10^{-4}$ DALY). In the overall ecosystem quality, duct types #1, #2, #3 and #5 were the least favourable, generating the greatest impacts in the global warming category of terrestrial ecosystems (GWTE, $5.1{\cdot}10^{-7}$ species·yr, $5.4{\cdot}10^{-7}$ species·yr, $5.9{\cdot}10^{-7}$ species·yr and $5.5{\cdot}10^{-7}$ species·yr). Finally, for the characterization of resource scarcity, duct type #2 was the most damaging, and presented the highest score in the category of fossil resource depletion (FRS, 1.43 €).

Figure 4 shows the results of the internal standardization process. The 100% value was assigned to the system with the highest score in each category. The proportion of the impact of the remaining systems was established from this re-scaling process.

Analyzed by impact category, duct types #3, #4, #6 and #11 presented the maximum values in most of the categories. Type #3 presented the maximum values in the categories of global warming in relation to human health (GWHH), stratospheric ozone depletion (SODP), ionizing radiation (IR) and land use (LU); type #4 in human carcinogenic toxicity (HCT), water consumption in relation to human health (WCHH) and terrestrial acidification (TA); type #6 in water consumption in relation to aquatic ecosystems (WCAE), depletion of mineral resources (MRS) and fossil resource depletion (FRS); and type #11 in ozone formation in relation to human health (OFHH), global warming in relation to freshwater ecosystems (GWFE), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial eco-toxicity (TE) and freshwater eco-toxicity (FEC). In general, the rest of the systems presented similar values of relative importance in each impact category.

Results according to the midpoint approach

Figure 5 shows the results of the individual scoring of the different duct types for the midpoint categories. One observes that the category of non-carcinogenic human toxicity presented the greatest values for all duct types.

Duct type #11 stands out as the most damaging to the environment when considering all categories. The most important categories were (in decreasing order) non-carcinogenic human toxicity (2.00 pt), global warming relative to human health (0.39 pt), carcinogenic human toxicity (0.34 pt), marine eco-toxicity (0.12 pt), global warming in relation to terrestrial ecosystems (0.08 pt) and fine particulate formation (0.04 pt).

Results according to the endpoint approach

Figure 6 shows the damage evaluation by protection area as an intermediate step to obtaining the single score in the

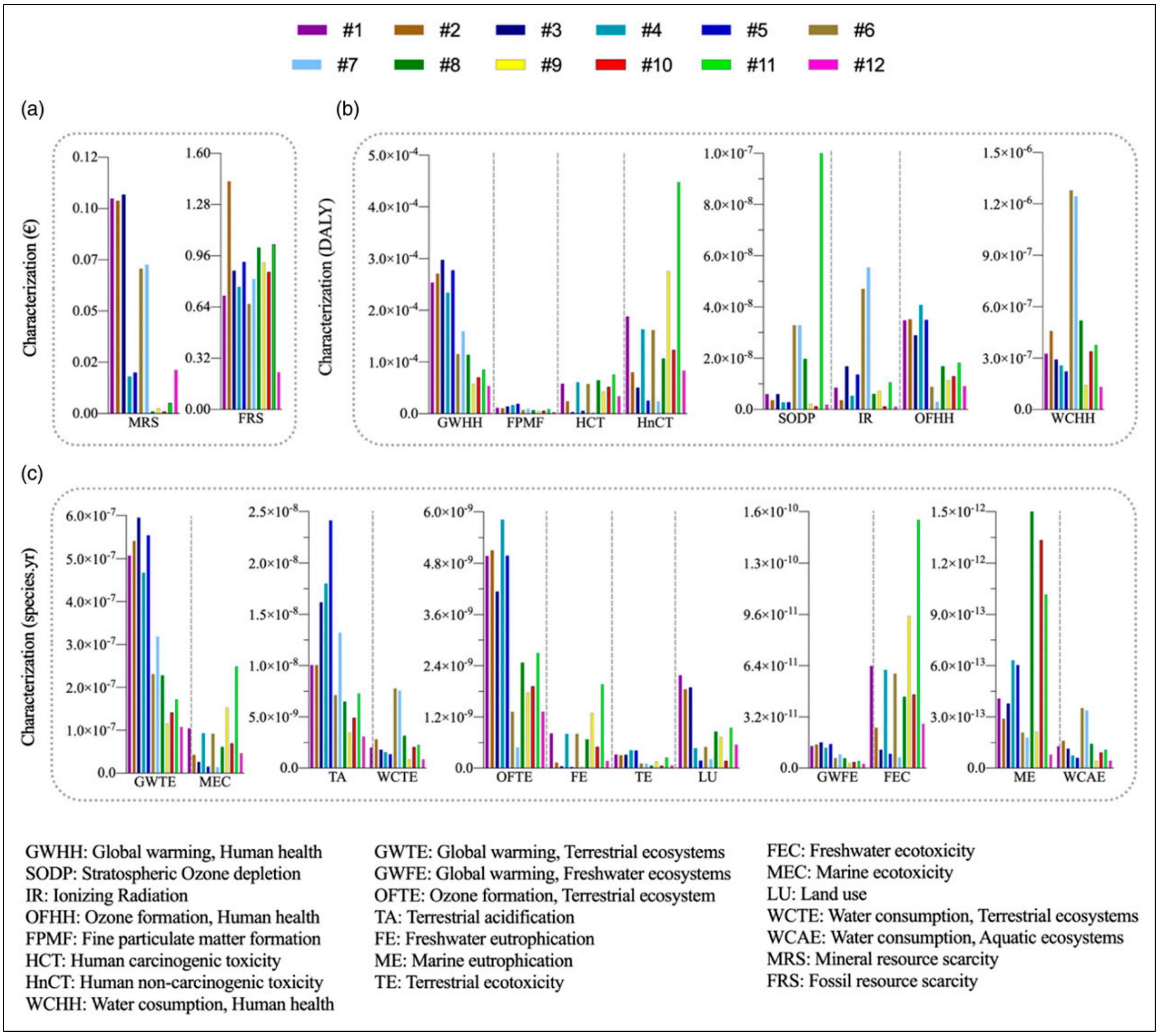


Figure 3. Characterization of impact categories.

endpoint approach. With respect to the damage to people's health, the value for duct type #11 ($6.2{\cdot}10^{-4}$ DALY) was 1.9 times superior to the mean ($3.3{\cdot}10^{-4} \pm 1{\cdot}10^{-4}$) of the other eleven types. It was followed by duct type #1 with $5.1{\cdot}10^{-4}$ DALY, and in third place duct type #4 with $4.7{\cdot}10^{-4}$ DALY. For damage to ecosystem quality, the value for duct type #3 ($6.5{\cdot}10^{-7}$ species·yr) was 1.0 times superior to the mean of the other types ($5.4{\cdot}10^{-7} \pm 1.2{\cdot}10^{-7}$). It was followed by duct types #1, #2, #4 and #5 with values very similar to each other. Finally, duct type #2 (1.66 €) was the one that most affected the scarcity of resources, its value being 1.2 times superior to the mean of the other types (0.9 ± 0.1 €). As in the previous protection area, the other types had similar impacts, with the exception of #12.

Figure 7 shows the single score results for each HVAC duct proposal after standardizing and weighting the characterization factors. In this way, it is possible to compare the systems by aggregating the impacts in the protection zones. The least favourable duct type is the one corresponding to polyisocyanurate since it has an impact of 3.00 pt/m^2 of HVAC system duct, of which 2.78 are attributable to human health (93%), 0.21 to ecosystems (6.7%) and 0.01 to the resource scarcity (0.3%). Duct type #12 gave the most desirable data on environmental impact with 0.86 pt/m^2 of HVAC duct, of which 90% were for human health, 9% for ecosystems and 1% for resources. It can be seen that the resource protection area suffered hardly any impact from any of the duct types. As one sees in Figure 3, the single endpoint score result makes sense since, for the midpoint, the values of non-carcinogenic human toxicity and global warming in relation to human health were much greater than those of the other impact categories.

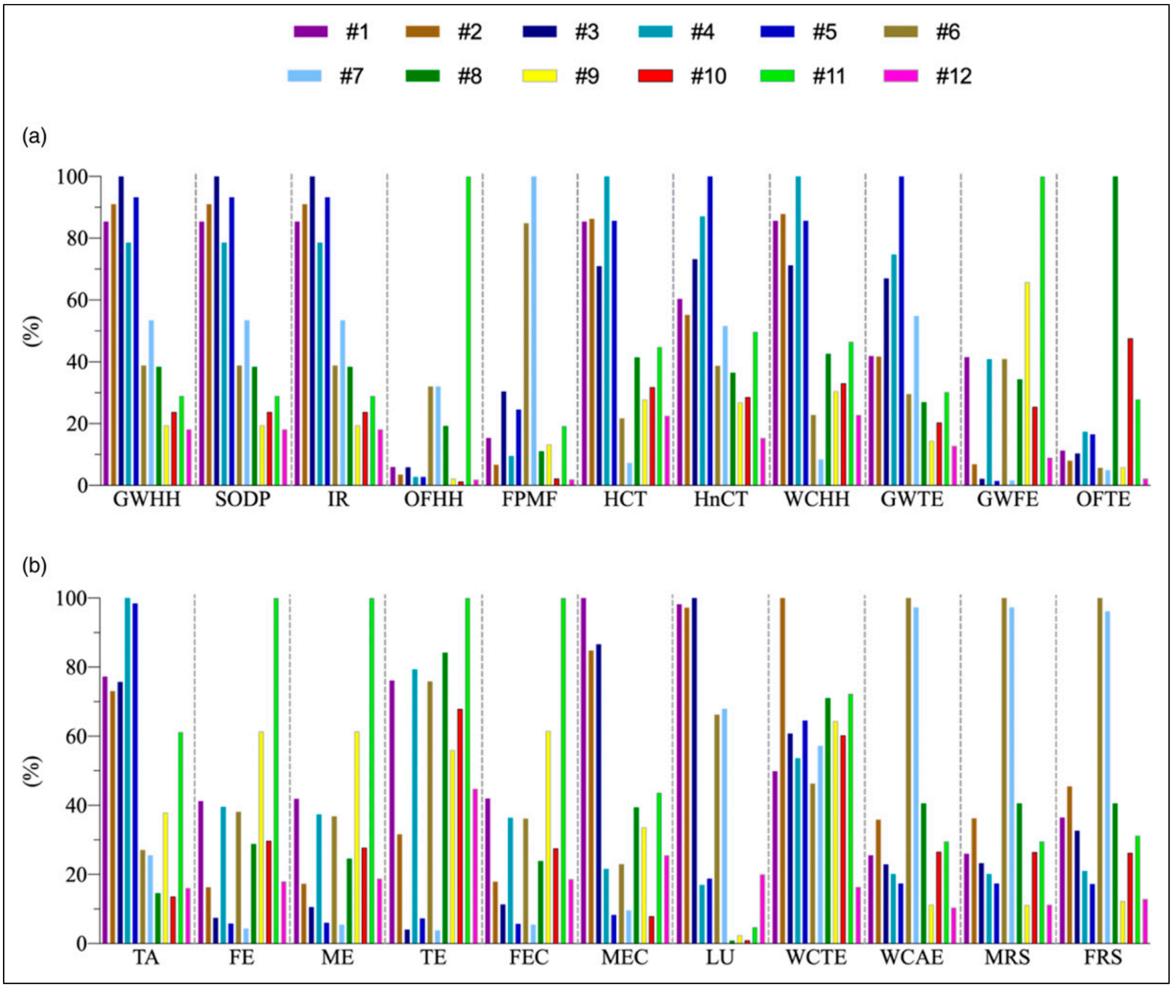


Figure 4. Internally standardized characterization of intermediate impact categories.

Economic and labour time results. Figure 8 shows the cost and labour time that have to be invested per functional unit of each duct type. With respect to cost, duct types #6 and #7 presented the greatest unit price (87.32 €/m^2 and 84.00 €/m^2, respectively), which are 1.56 and 1.50 times greater, respectively, than the following type, #4, at 56.05 €/m^2. The lowest installation cost was for type #12 (23.98 €/m^2), followed by type #9 (24.12 €/m^2). With respect to the labour time, type #12 (0.6 h/m^2) was the fastest in execution and types #1 - #5 were the slowest (1.1 h/m^2). Duct type #12 minimized both dimensions (cost and time) with 23.98 €/m^2 and 0.6 h/m^2.

Discussion

The current pandemic situation caused by the COVID-19 crisis requires health systems that are efficient, clean (free of viruses and bacteria), safe and with low environmental impact.[60,61] The LCA methodology has been found to be suitable for making environmental impact comparisons of different types of HVAC air ducts in healthcare buildings. This methodology is based on the ReCiPe 2016 environmental assessment method and criteria, as well as the LCA framework shown in Figure 1. Thus, it quantifies the environmental impacts through 22 impact categories and 3 areas of protection. This method is based on the variables described in the life cycle inventory (type of material, density, thermal conductivity and quantity of material), those referring to transport (type of transport and transport distance) and energy consumption (type of consumption and quantity consumed). Therefore, this research will contribute to attaining the sustainability goals and strategies set out by the European Commission and the United Nations.[62,63] The results will help architects, engineers and infrastructure managers to select the most suitable type of HVAC ductwork, considering the perspective of sustainability. In the engineering context, decisions are usually made with economic, ease of execution and reliability criteria.[64] However, this study has incorporated sustainability and care for the environment into this decision-

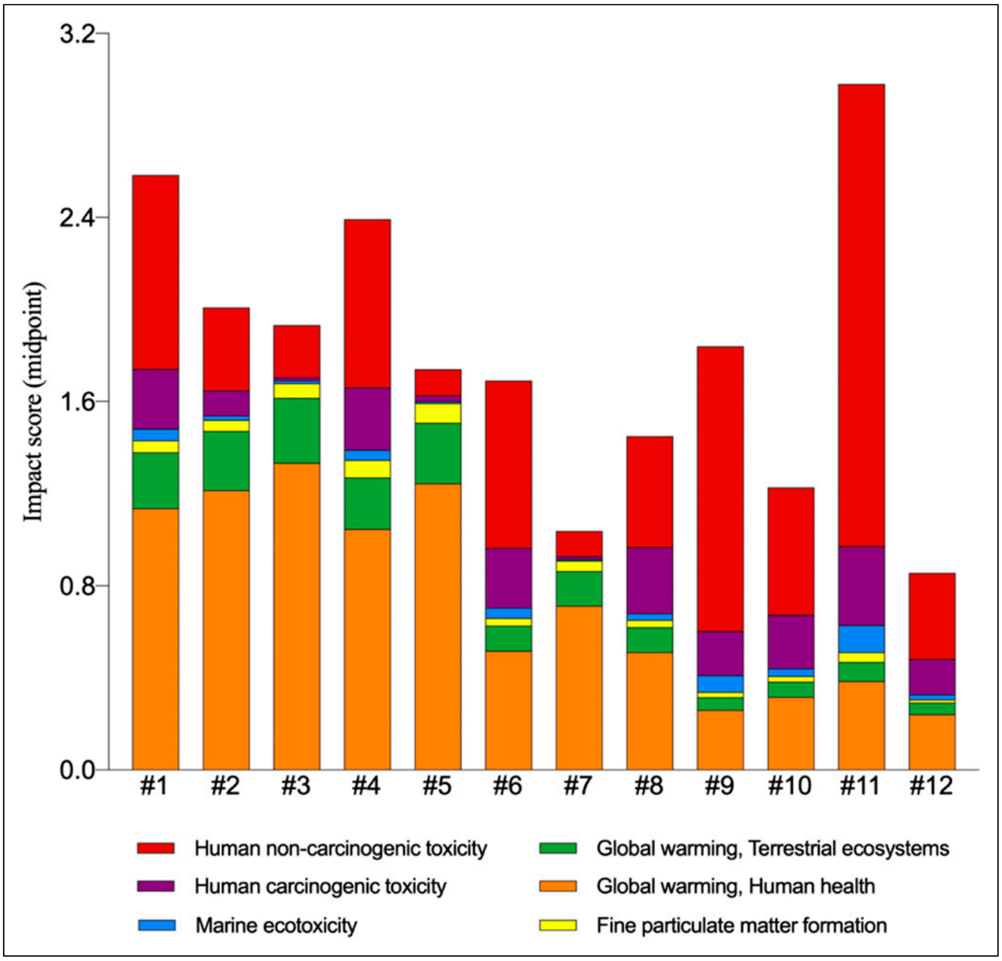


Figure 5. Impact analysis – unique midpoint score.

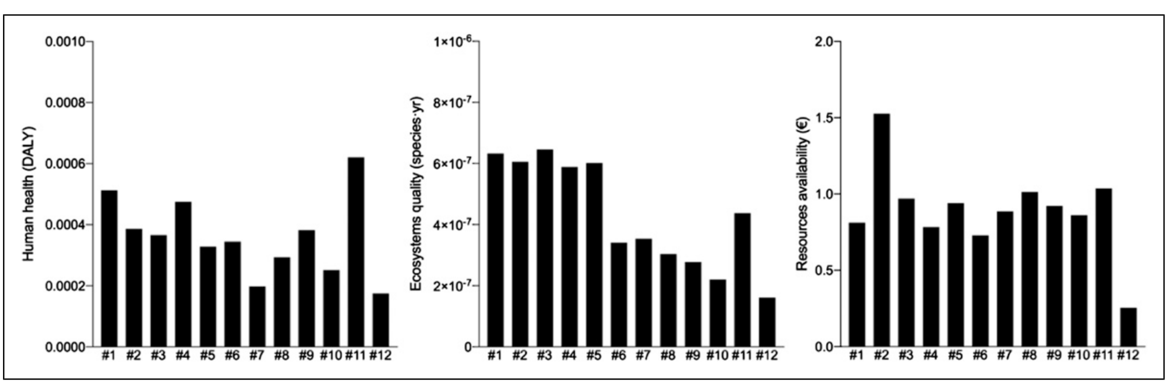


Figure 6. Damage assessment by protection areas.

making process. In this way, it will be possible to make a more objective decision when selecting ducts for the HVAC systems of healthcare buildings.

The aluminium HVAC duct type with helical steel wire reinforcement and fibreglass insulation (#12) had the best environmental results. Despite these advantages, it is unsuitable as it presents a series of drawbacks during its useful life that are unacceptable due to the critical activity of healthcare buildings. It requires good fasteners so that no bends or uncalculated/unplanned positions might arise that

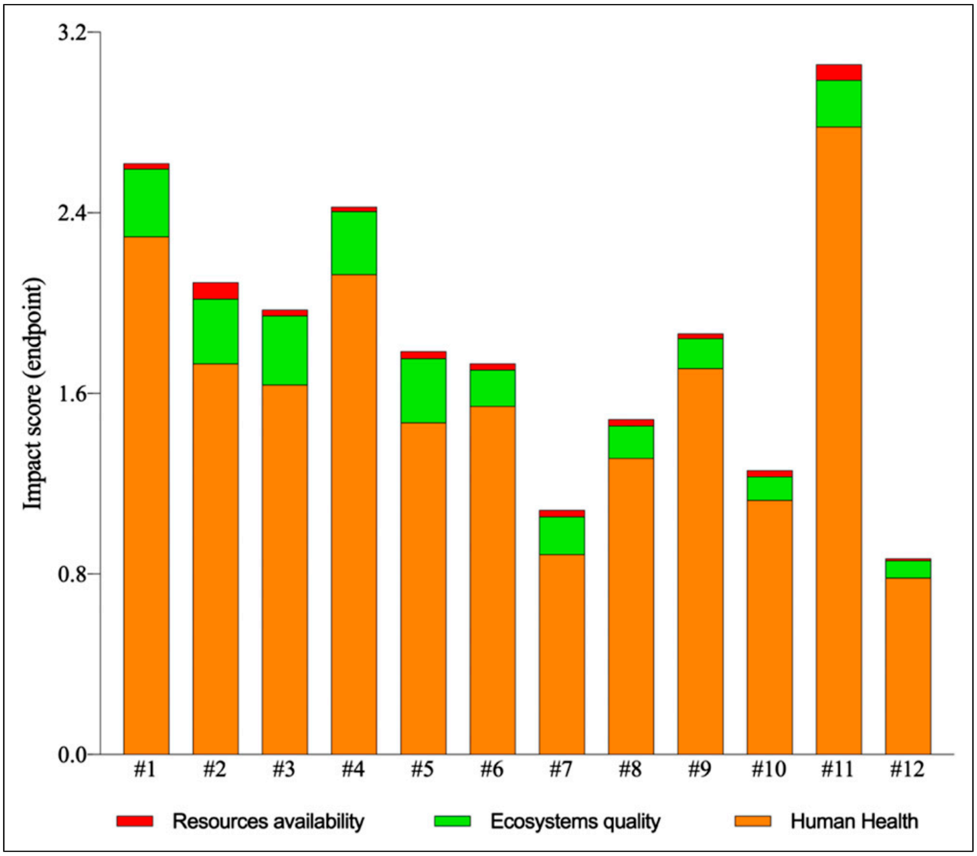


Figure 7. Impact analysis – unique endpoint score.

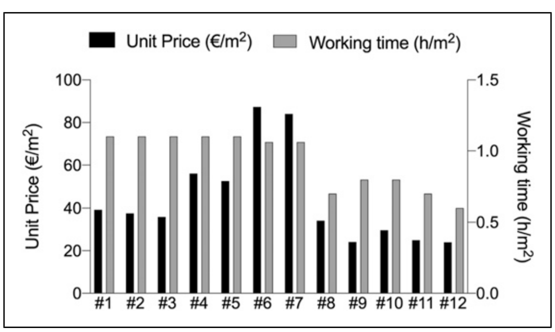


Figure 8. Unit price and labour time for the installation of the duct functional unit.

would obstruct the airflow and cause pressure losses in the distribution channels.[65] These ducts are vulnerable to cuts or cracks, which would lead to the appearance of leaks and the corresponding loss of pressure and efficiency.[66] In addition, it should be noted that they require large duct sizes, which in turn would increase any pressure losses. The characteristic roughness of this duct type causes friction against the airflow, which is negatively associated with the compression ratio of the HVAC system.[67] Finally, it is a duct type with a greater predisposition to bacterial proliferation and is harder to clean than other metallic types such as galvanized steel.[68]

The duct type of copper sheeting with rock wool insulation (#7) is the second in terms of the most favourable environmental impact values. It requires an insulation thickness of 51 mm to achieve the same thermal properties as duct type #12, and the environmental impact values are consequently less favourable than those of type #12. It is a highly viable option for projects in hospitals since copper reduces the microbial load by up to 99.97% compared with other metallic materials such as aluminium or steel.[69,70] This fact makes it possible to reduce the relationship of HVAC systems with the proliferation of nosocomial diseases in critical wards by guaranteeing/favouring their clean-room condition.[71] Nonetheless, this type (#7) had the greatest cost (72% more than type #12) and labour time (43.5% more than type #12).

An alternative solution to types #7 and #12 is the polyurethane type (#10). Both the labour time and the unit price are greater than those of type #12 and less than those of type #7. Nonetheless, its environmental impact values allowed it to be categorized as a favourable solution. One aspect to take into account is that it is harder to carry out effective cleaning for this duct type compared to sheet metal solutions due to its surface roughness and its lack of self-supporting capacity.[68]

The polyisocyanurate duct type (#11) had the poorest environmental indicators mainly due to its chemical composition. The studies carried out by Lacasta et al.[72] indicate that, in case of fire, this type of duct gives off very high values of hydrogen cyanide (HCN) and carbon monoxide (CO) compared with other materials. In addition, this material has a very low flash point, which enhances the risk of fire.[73] Nonetheless, it has a low labour cost, being the second cheapest, with a low/medium installation time.

Duct types #1 and #4 were the following in the classification of least desirable solutions in terms of environmental impact. They had fairly similar environmental impacts, both globally and by protection areas. In economic terms, type #1 was inferior to type #4, with the differences relative to the most expensive (#6) being 30% and 55%, respectively. In terms of labour time, the two types were equal. Therefore, of these two duct types, #1 would be more favourable. On the other hand, it must be taken into account that, due to the protective treatment it has undergone, galvanized steel is one of the metal types, together with copper, at the lowest risk of suffering corrosion.[74] Corrosion is a very dangerous chemical reaction for ducts as it can produce very damaging effects such as loss of self-supporting capacity, cracks, structural fatigue, etc.[75] All these imply a loss of the system's efficiency in addition to the possibility of the HVAC system's rupture in the case of no remedial procedure having been instituted.

Duct types #2, #3, #5, #6 and #9 had very similar global impact levels, with types #2 and #9 being greater in the category of human health and types #6 and #9 lower in the category of ecosystem quality than the rest. In economic terms, type #6 was the least favourable, followed by #5 with values around 40% cheaper. In terms of labour time, the fastest type of the group was #9 by around 27% compared to the rest of the group.

Of all the HVAC air duct types analyzed, the copper sheeting solution with rock wool insulation was found to be the optimal solution for healthcare buildings. This type presents the second most favourable result in terms of environmental impact. Despite its high cost and intermediate labour time, it is the most favourable solution in terms of health requirements and environmental impact. This fact is the most important for healthcare buildings since the health of patients and users of their facilities is at stake. Thus, the health requirements associated with the technical dimension have been prioritized over the other dimensions of the multidimensional analytical process. This is followed by the environmental dimension, which has been shown to be critical in reducing the environmental impact associated with healthcare infrastructure and prioritized with respect to costs and execution times. Table 3 shows the multidimensional comparative analysis carried out in this research.

The present results concur with those of Shirazi et al.[76] which are based on the fact that the flexible duct type is the solution that offers the least environmental impact. Thus, these authors demonstrated reductions in construction impact of up to 45% when using the flexible duct type. In the case of this research, the improvement ranges are slightly lower (39.88%). This is mainly due to the use of a more updated version of the LCA software (SimaPro 9) and the selection of a different impact analysis method, leading to different characterization, normalization and/or weighting patterns.[77] Nonetheless, as already stated, this solution cannot be recommended for healthcare buildings.

In their study on the embodied carbon of HVAC systems, Kiamili et al.[78] developed a life cycle analysis of the different elements that make up these systems. They obtained impacts of approximately 74 kg CO_2 eq/m^2 for the total ductwork present in the building and composed mainly of galvanized steel and copper with fibreglass and mineral wool insulation. In contrast, this research has obtained an average value of approximately 17 kg CO_2 eq/m^2 for the same HVAC duct typologies. Therefore, there is a significant difference between the two studies, which is mainly due to the adoption of different functional units (m^2 A_{temp} and m^2 of HVAC duct, respectively). In addition, different models and databases have been used, so that the assignment of impact values is different. Nevertheless, similarities can be observed in the methodologies and workflows followed in the two investigations, which are in line with the recommendations of the ISO 14040 and ISO 14044 framework. Finally, a greater similarity can be observed when comparing the results of the galvanized steel and fibreglass insulated HVAC ducts of this research (22 kg CO_2 eq/m^2), with those obtained by the author Fong et al.[79] in their LCA study on different ventilation methods (28 kg CO_2 eq/m^2). This is mainly due to the use of the same functional unit (m^2 of HVAC duct) and environmental database (Ecoinvent). However, a slight difference is observed due to the use of different insulation thicknesses (38 mm and 50 mm, respectively).

The potential for application of this research increases with the appearance of new healthcare buildings requirements, new user comfort features and the growing need to replace systems that are obsolete, damaged, inefficient or harmful for human health including the reformation or replacement of their HVAC facilities.[80,81] Therefore, when choosing materials, it is important to take into account the impact that the reform will have on the environmental biosecurity of the installation.[82] In addition, recent studies have shown the dependence between environmental impact and thermal comfort. In these studies, air temperature, radiation across the duct surface, moisture and velocity have been identified as the most environmentally penalizing factors.[83,84]

In developing countries, the purchasing power and the transport of materials are also aspects that need to be taken

Table 3. Main advantages and drawbacks of the analyzed ductworks.

Case	Advantages	Drawbacks
#1	1. Low cost 2. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system	1. High environmental impact 2. Long labour time
#2	1. Low cost 2. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system	1. Significant environmental impact 2. Long labour time
#3	1. Low cost 2. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system	1. Significant environmental impact 2. Long labour time
#4	1. Average cost 2. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system	1. High environmental impact 2. Long labour time
#5	1. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system	1. Significant environmental impact 2. Long labour time 3. High cost
#6	1. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system 2. Significant reduction of microbial load 3. Fire resistant	1. Significant environmental impact 2. Long labour time 3. High cost
#7	1. Low environmental impact 2. Significant reduction of microbial load 3. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system 4. Fire resistant	1. High cost 2. Significant labour time
#8	1. Low cost 2. Low labour time 3. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system 4. Fire resistant	1. Significant environmental impact 2. Difficult to clean. Associated with bacterial growth
#9	1. Low cost 2. Low labour time 3. Fire resistant	1. High environmental impact 2. High surface roughness. Associated with poor compression ratios of the HVAC system 3. Difficult to clean. Associated with bacterial growth 4. Low self-supporting capacity
#10	1. Low environmental impact 2. Low cost 3. Average labour time	1. Low self-supporting capacity 2. High surface roughness. Associated with poor compression ratios of the HVAC system 3. Difficult to clean. Associated with bacterial growth

(continued)

Table 3. (continued)

Case	Advantages	Drawbacks
#11	1. Low cost 2. Average labour time 3. High resistance to corrosion. Favouring the reduction of potential risks (loss of self-supporting capacity, appearance of cracks and/or structural fatigue) and improving the efficiency of the system	1. High environmental impact 2. High flammability. Associated with a high fire risk 3. In case of fire, high emissions of HCN and CO 4. High surface roughness. Associated with poor compression ratios of the HVAC system 5. Difficult to clean. Associated with bacterial growth
#12	1. Low environmental impact 2. Low cost 3. Low labour time	1. Difficult to fix. Prone to airflow anomalies and pressure losses 2. High vulnerability to cracking or cutting 3. Large diameters. This fact favours pressure losses 4. High surface roughness. Associated with poor compression ratios of the HVAC system 5. Difficult to clean. Associated with bacterial growth

into account since there may be types of ductworks that are beyond those countries' reach.

The methodology used in this research, based on the framework described in Figure 1, has several advantages. This methodology is widely contrasted in the scientific literature and employs a dual midpoint-endpoint approach typical of the ReCiPe 2016 method and a 'cradle to grave' life cycle scenario.[85] This duality increases the scope of the results obtained by offering two LCA perspectives. The 'cradle to grave' scenario is one of the most comprehensive in terms of the life cycle, as it covers a more detailed time span of the element, process or system under analysis and increases the possibilities for comparison at different stages. However, the globalization of the weighting and normalization factors used in the ReCiPe 2016 methodology does not allow the analyses to be adapted to all scenarios, limiting the precision of the results obtained. Furthermore, any adaptation of the study for another country could lead to slight variations in the environmental impact results obtained due to modifications in the construction processes and transport routes. However, this case study is applicable to any healthcare building whose health requirements are similar to those in Spain. Thus, a solution is offered that significantly reduces the environmental impact associated with HVAC systems and consequently the healthcare infrastructure. This is one of the biggest sources of environmental impact in the world.[86]

Future work should focus on the environmental assessment of other components of the HVAC system, for example, water pipes, grilles and diffusers. It is also important to identify and evaluate recycled materials that can be incorporated into HVAC ducts to minimize their environmental impact. This allows for a further reduction of the environmental footprint associated with one of the facilities in healthcare buildings of greatest demand and consumption. Furthermore, different recycling strategies should be studied to establish the optimal solution based on the type of duct used. Finally, it would be interesting to analyze the relationship between the energy efficiency of HVAC systems and their life cycle analysis (LCA), assessing the increase in environmental impact associated with the increase in insulation. All this will allow the reduction of the impact associated with the HVAC facility and, consequently, the total impact of the building.

Conclusions

This research has compared the types of HVAC air ducts most suitable for healthcare buildings in terms of cost and labour time, environmental impact and the health requirements of their operation. Thus, for restrictive health requirements imposed on healthcare buildings, an LCA analysis of 12 HVAC duct types was carried out following a bottom-up method based on the ISO 14040 and ISO 14044 norms within a 'cradle to grave' perspective. Furthermore, once the environmental impacts of the different HVAC duct typologies had been quantified, the analysis was complemented by including the dimensions of cost and execution time. Thus, this research offers a multidimensional analysis of the different HVAC duct typologies present in the healthcare infrastructure in Spain. In this way, the objective is to offer the optimal solution based on the different dimensions previously described, giving preference to the environmental dimension due to strict sanitary requirements previously established.

The results showed that the duct types of aluminium with helical steel wire reinforcement and fibreglass insulation (#12), copper sheeting with rock wool insulation (#7) and polyurethane (#10) were the most favourable in the different categories of environmental impact analyzed. Of these, the copper duct type with rock wool insulation (#7) was found to be the most interesting for healthcare buildings. This type of duct was the second most environmentally respectful, being 2.83 times more respectful than the least favourable (#11). However, its unit price was the most expensive, and its labour time was an intermediate one compared to the other solutions. Despite these factors, it was found to be the optimal construction solution for buildings with high sanitary and comfort requirements for their HVAC systems. This is the case in critical hospital wards, with rooms that need to maintain low microbial loads due to the operations that take place inside them. In addition, HVAC systems in healthcare buildings tend to demand large amounts of energy. Therefore, a duct type with low surface roughness and that is easy to clean is recommendable from the point of view of energy efficiency.

Finally, the main limitation of this study is that its focus is on the ducts of HVAC systems, without taking the rest of the system's components into account. Therefore, these studies should be extended to the other components so that their environmental impact can be reduced to the minimum.

Author's contribution

Conceptualization: GSC; data curation: GD; formal analysis: GSC, BA; funding acquisition: GSC; investigation: GSC, BA, GD; methodology: GSC, BA; project administration: GD; resources: BA; software: BA; supervision: GSC; validation: GSC; visualization: BA; roles/writing – original draft: BA; writing – review and editing: GSC.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the European Regional Development Fund provided through Research Projects GR18029 and GR21098 linked to the VI Regional Plan for Research, Technical Development, and Innovation from the Regional Government of Extremadura (Spain).

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