A Life Cycle Analysis of ionizing radiation shielding construction systems in healthcare buildings [1]

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Abstract

Optimization of material resources, energy efficiency and reduction of environmental impact are basic aspects in selection of a construction system. The aim of this study is to evaluate the environmental impact generated by different shielding systems for walls of an X-ray room in healthcare buildings. Eight commercial construction systems for anti-X shielding were analysed. A Life Cycle Assessment (LCA) was performed by SimaPro using the Ecoinvent database, and a single-score damage category analysis was performed for midpoint and endpoint levels. Prices of installation and working time employed in the construction of a functional unit of each system were obtained. Solutions with clay brick, cast-in-place reinforced concrete and sprayed concrete were the most favourable for the different categories. Sprayed concrete obtained 6.739 points/m^2 of against 165.12 points/m^2 of rolled steel option. The damage to human health occupies between 41% and 87% of the total impact in the protection areas. The impact category of human toxicity is also the broadest in the midpoint approach. Considering time and cost of implementation, clay brick solutions proved to be the most favourable, along with cast-in-place reinforced concrete and barite concrete. System #6 is the most environmentally friendly, 1.6 times less than the next one (which is #4), although its unit price is 1.94 times the cheapest (which is #2) and its execution time is 1.89 times the lowest (which is #2 again). The knowledge generated in this study will improve investment decision making for the planning departments of the Sanitary Systems, obtaining an economic, social and environmental benefit. The main novelty of the work lies in the object of the study (X-ray room) as well as in the integration of LCA and economic aspects.

Keywords: Healthcare design; Building materials; Healthcare Buildings; Sustainable radioactive shielding systems; Healthcare Engineering

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1 Introduction

The design and construction of an X-ray facility for medical diagnostic purposes must be safe for people. The radiation-equivalent doses that may be received by exposed personnel, patients, and accompanying persons should be as low as reasonably achievable [1]. Therefore, the armour of an X-ray room plays a critical role in absorbing as much radiation produced by these equipment as possible, to avoid it from being transmitted perimetrically [2]. In order to provide this mitigation of radioactivity, different materials are used: lead, steel, concrete, ceramics, among others. Each of these materials offers different advantages and disadvantages from a point of view of placement, costs, thickness, etc. In addition, these materials have a different impact on the environment. Lead is commonly used for anti-X shield. However, its use can cause harmful effects on people's health [3,4] and on the environment [5].

Conventional radiography equipment emits X-rays that cause adverse effects on workers in the room itself and other people in adjacent wards [6]. X-ray technicians at these facilities must carry individual protection equipment (IPE), personal radiation monitoring dosimeter and they must adjust their workload to minimize their exposure [3]. Other workers and users outside the room do not carry IPE, so the vertical walls enclosing the diagnostic X-ray machine must have radiological isolation characteristics that attenuate X-ray transmission to the outside of the room [2].

The doses emitted by diagnostic X-ray machines vary considerably depending on the angle of incidence of the beam [7] and its diagnostic application [8]. Radiopacity is achieved by superimposing layers of materials with anti-radiation properties of a certain thickness, so that a lead equivalent is achieved according to test IEC 6133-1:2014 [9]. Consequently, designing construction systems for protection against ionizing radiation is one of the complex problems faced by Healthcare Engineering [10]. In Spain, Nuclear Safety Council is the competent authority in this area, which has published various technical guides for the protection of exposure of people [11] applying commonly accepted experience-based design methods [12,13].

Research in this area of work has been focused on demonstrating the radiation attenuation capabilities of different materials. In this way, concrete can achieve anti-radiation properties by increasing its density through the incorporation of heavy aggregates and metal reinforcement (reinforced concrete) or incorporating additives such as barite sulphate ($BaSO_4$) [14]. Other equally valid materials can be drywall [15], barite plasterboard [16] and steel [17]. There are even ceramic materials that have anti-radiation properties [18].

In order to achieve sustainability, the environmental dimension must be incorporated into the choice of construction materials and construction systems for radiological shields [19]. Life Cycle Assessment (LCA) is a quantitative method to evaluate the environmental and human health impact over the lifetime of a product, taking into account extraction and processing of raw materials, manufacturing, distribution, use, maintenance and repair, and disposal [20].

Notwithstanding, the evaluation of hospital infrastructures construction has not yet been widely addressed in the literature from an environmental perspective. Hui Li *et al.* [21] proved that hospital buildings have the highest environmental impact compared to residential, commercial and educational buildings. Regarding conventional radiology rooms, Lopresti *et al.* [22] investigated new epoxy-based lead-metal substitute materials with similar radiopacity properties. Despite the current knowledge, the study of radiology room shielding systems in healthcare buildings from an environmental perspective using LCA tools has not been carried out.

The main objective of this study is to evaluate the environmental impact generated over the cradle-to-grave life cycle of different wall shielding systems used in healthcare buildings' X-ray rooms, and to analyse their feasibility from an environmental perspective. In this way, architects, engineers and infrastructure managers will have a tool to select the construction system considering sustainability.

This work is aligned with the achievement of the Sustainable Development Goals (SDG), the work agenda set by the United Nations for the period 2015-2030 [23]. Building hospitals in a sustainable way is clearly within SDG no. 3: “ensuring healthy and safe living for all ages,” but it is also related to SDG no. 9: “building resilient infrastructure,” SDG no. 11, about more inclusive, safe, resilient and sustainable cities, SDG no. 12 sustainable consumption and production, combating climate change (SDG no. 13) [24].

2 Literature review

In environmental management, internationally accepted standards describing the LCA process are ISO 14040 [25], which sets out principles and framework, and ISO 14044 [26], which describes requirements and guidelines for carrying it out.

Uncertainty management of knowledge about environmental mechanisms revolves around Cultural Theory [27]. Individualist, Hierarchist and Egalitarian archetypes assume a short-, medium- and long-term perspective on the atmospheric lifetime scale of substances. The environmental damages identified by LCA are congruent with an egalitarian worldview [28]. Cradle-to-grave approach follows the linear economic model of product use from raw material extraction to product use and disposal [20].

Applying LCA to construction, Maria de Souza *et al* [29] conducted an LCA-based evaluation to compare ceramic brick exterior wall with concrete bricks and cast-in-place reinforced concrete. They found that environmental impact of the first one is 50-70% lower than the third one in the three areas of protection: climate change, human health and ecosystem quality. Ingrao *et al.* [30] identified the most sustainable solution for exterior walls according to the midpoint and endpoint approach. There are extensive reviews of LCA in the construction sector [31], on residential and commercial buildings [32], applied to renovation work [33] and even in the demolition process [34,35].

LCA has been proven as the right tool for analysing the environmental impact associated with the life cycle of buildings [36]. In hospital environment it has been used to measure environmental impact generated by different products and processes. For example, McGain *et al.* studied the environmental impact associated with the life cycle of an anaesthesia equipment. [37], of a catheter insertion kit [38] and of a plastic anaesthetic drug trays [39]. Igos *et al.* analysed the environmental impact of wastewater from sanitary buildings [40] y studied the elimination of pharmaceuticals [41]. Furthermore, García-Sanz-Calcedo *et al.* demonstrated the high potential for global warming associated with the construction of health centres [42] and the influence of the management of the energy consumption of a hospital with the reduction of its environmental impact [43].

Different databases are available to perform Life Cycle Inventory (LCI) in building industry. Lasvaux *et al.* [44] compared the generic (such as Ecoinvent, GaBi, DEAM, US-LC, etc.) and product-specific (i.e., Product Category Rules) databases in construction sector and listed the benefits of Ecoinvent database in France. Martínez-Rocamora *et al.* [45] found that Ecoinvent and GaBi databases showed the best features (scope, completeness, transparency, comprehensiveness, update and license) in construction sector among European, American, national, input-output and other databases. Althaus *et al.* [46] also noted that Ecoinvent database is suitable for building materials. Ecoinvent is one of the most widely used databases for LCI. In fact, a comprehensive review of LCA between 1995 and 2008 indicated that 59% of authors employed this data repository [47].

In order to develop the Life Cycle Impact Assessment (LCIA), ReCiPe is a method frequently used. Data from LIC is converted into impacts through this method by using 18 midpoints indicators and 3 endpoints indicators [48]. Bories *et al.* [49] evaluated the environmental impact of porous fired clay bricks with bio-based additives; Pushkar and Verbitsky [50] analysed environmental damage of four wall technologies; and Kono *et al.* [51] evaluated different thermal insulation materials using ReCiPe.

Output of ReCiPe method is the valuation of metrics (points) called eco-indicators midpoint (problem oriented) and endpoint (damage oriented) [20]. Problem-oriented approach is associated with a low level of uncertainty but implies greater difficulty of interpretation due to the high number of impact categories. The opposite is true for damage-oriented approach. Controversy exists among experts. Nevertheless, Bare *et al.* [52] suggested that both methods could be used together to provide more information to decision-makers.

This paper aims to address a gap in the scientific literature of hospital engineering. To the best of our knowledge, life cycle analysis of X-ray rooms has not been carried out. In the paper the different solutions are analysed both from an economic and environmental point of view. The paper addresses two issues of great interest to the scientific community, on the one hand environmental concerns, one of the main challenges facing mankind, as well as health care. The current pandemic situation caused by the COVID19 crisis requires resilient health systems with low environmental impact.

3 Material and methods

3.1 General method

The multi-case LCA analysis followed a bottom-up methodology based on processes in accordance with ISO 14040 [25] and ISO 14044 [26] as shown in Fig. 1.

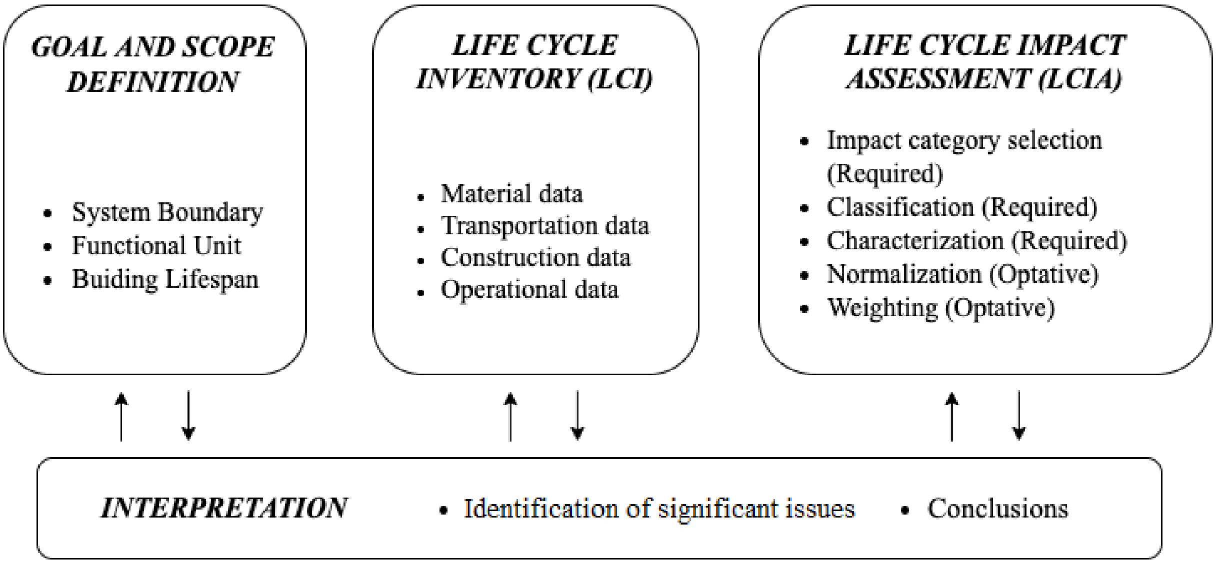


Fig. 1. Life Cycle Analysis framework. Adapted from [25]**.**

Goal and scope definition

Firstly, a comparative evaluation of the environmental impact of eight X-ray room shielding systems in hospitals was defined as an objective of the analysis. The functional unit chosen was 1 m^2 of shield for a radiology room in a hospital, being the most widely used parameter according to published scientific research [47]. The scope of the study (system boundary) in terms of life cycle stages covered raw materials extraction, manufacture of the materials to build the wall, transport to the hospital, implementation, useful life (25 years) and finally demolition, as shown in Fig. 2. LCI will be defined in Description cases section.

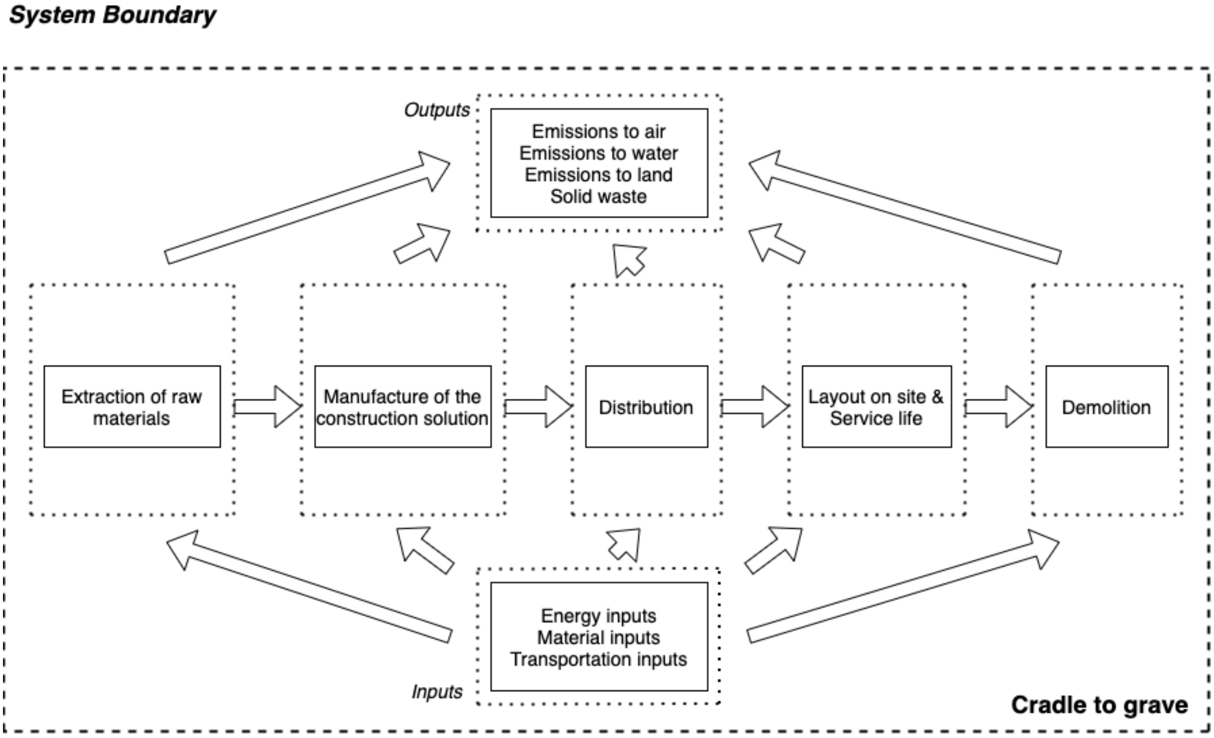


Fig. 2. System boundary under cradle-to-grave approach.

Life Cycle Impact Assessment

Once the LCI was established, the ReCiPe method for characterizing environmental impact in the life cycle was used as this method is representative on a global scale [48]. The impact assessment was quantified using SimaPro v8.1 [53] software and the egalitarian perspective was chosen to take into account an infinite time horizon in the most pessimistic development framework [54]. Double weighting indicators (midpoint and endpoint) were chosen to disaggregate the results by damage routes and check individual contributions to the impact on each protection area. ReCiPe proposes 18 impact categories, but SimaPro v8.1 includes marine eutrophication within freshwater eutrophication.

An outline of both approaches to impact assessment methodology followed in this work is shown in Fig. 3, which is a summary of the method and ReCiPe's own characterisation, normalisation and weighting factors [48].

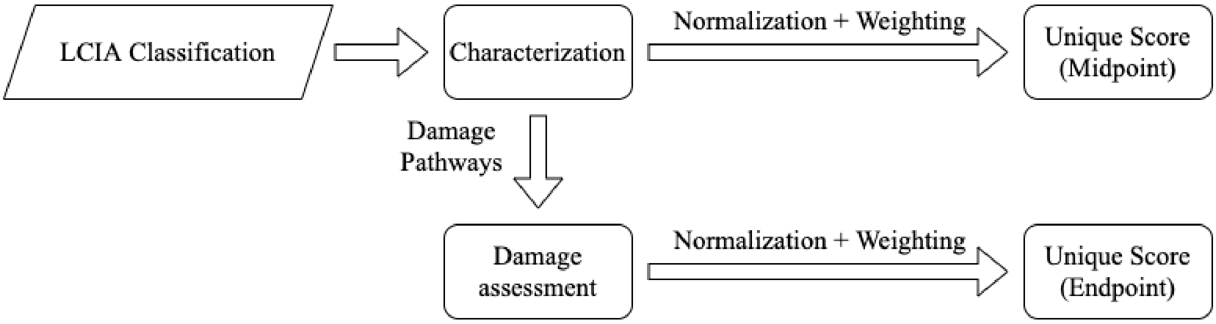


Fig. 3. Single score calculation process according to midpoint and endpoint approach.

For the selection of impact categories (midpoint), the RECIPE methodology points out the following aspects [55]:

- Impact categories must have direct environmental relevance.
- Impact categories are names, and category indicators are measurable aspects. Thus, characterization models are required.
- Impact categories capture the common mechanisms involved in the effect of various substances.

For the selection of the final level categories (endpoint), those that influence on policy and sustainable development are chosen. In the case of the methodology used: human health, environmental quality, and resource availability.

The characterization factors of each protection area were expressed in different metrics. For those referred to the human health, DALY (disability adjusted life years) was used, which represents the years lost by a person due to a disease; ecosystems quality, in species lost per unit of time; and, finally, for resource scarcity, as the extra cost of extracting resources in the future. The standardization of characterization factors was done with global scale references to ensure the extrapolation of results. Midpoint approach does not weight the normalization to achieve the final score. However, unique score was obtained by an endpoint approach through the damage and weighting route after normalization.

To complement the environmental impact analysis, other key dimensions for the decision to choose shielding systems were incorporated. For a given functional unit, cost and material execution time were obtained from unit prices of the necessary materials and the work performance of the necessary labour. These values were calculated from specialized databases of construction in Spain elaborated from information provided by manufacturers [56].

3.2 Description cases

An equipment with pipe power between 20 and 40 kW, maximum 125 kV, focal points of 1-2 m/m and filtration of 3 mm (Al), with a weekly load of 80 mA minutes per week, with a maximum field size of 40x40 cm was considered. The dose limits considered were 0.12 mSv/week for the radiologist work area and 0.02 mSv/week for the walkable area for patients and non-radiographic medical staff.

The dimensions of the X-ray room considered were 3.60 m wide and 5.40 m long, with a free height of 2.70 m. Fig. 4 shows the floor plan of this room.

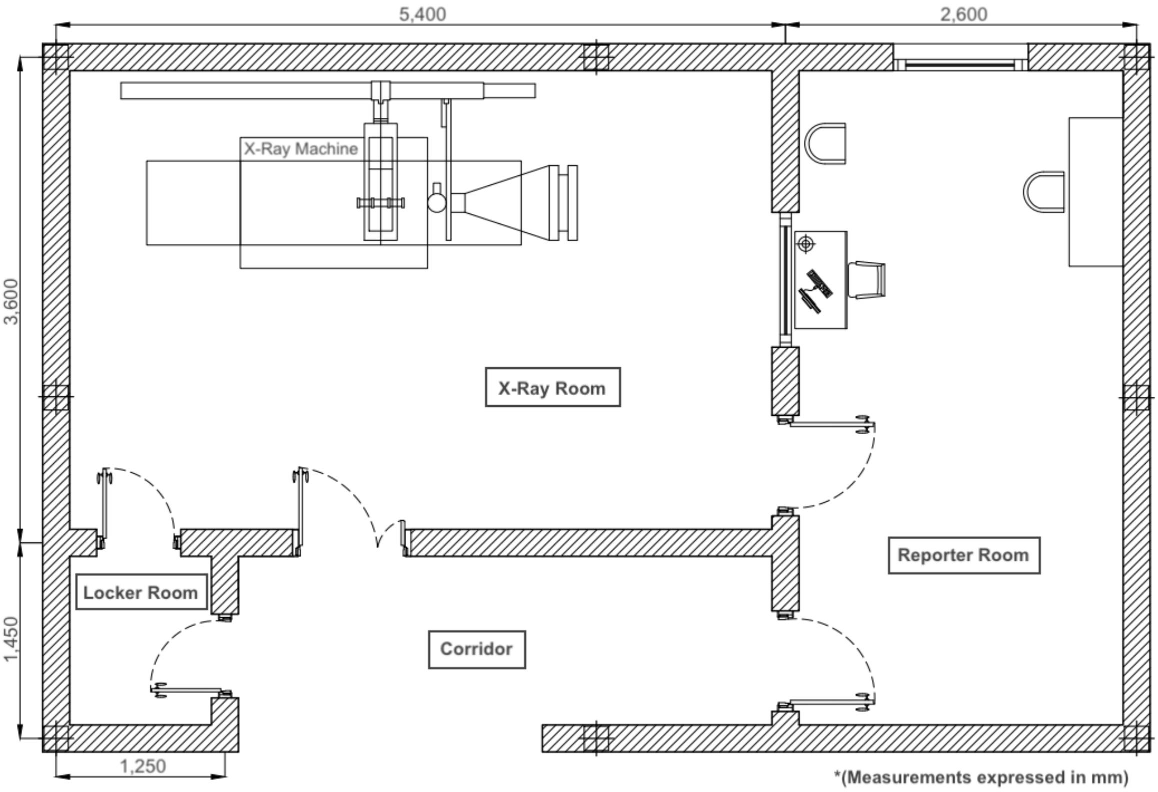


Fig. 4. Floor plan of an X-ray room.

Eight possible construction systems were considered for armouring (Table 1). The radioprotective walls are those that enclose the radiology machine and that separate the controlled zone from the monitored zone.

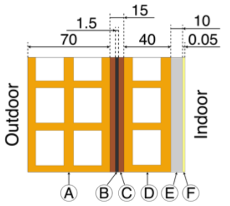
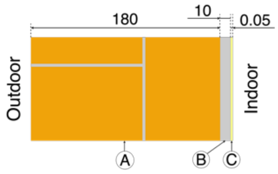
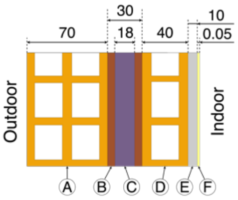
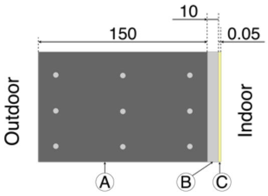
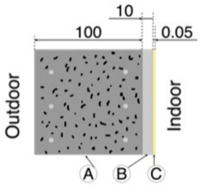
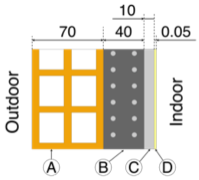
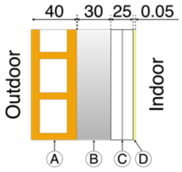
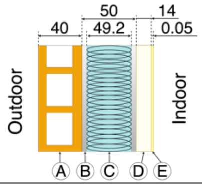
The thickness of the wall varied according to the construction material. The horizontal faces were not taken into account because they are structural elements and the isodoses curves in a vertical plane to the machine are of less intensity [57]. These systems were designed to ensure an individual dose cap on the other side of the shield by estimating the attenuation factor (A) of the Equation (1)

$$A = \frac{\Gamma \cdot W \cdot U \cdot T}{d^2 \cdot H_w} \tag{1}$$

where Γ is the equivalent radiation dose (in mSv) produced by a beam at 1 m, W is workload (mAs·min/week), U is the barrier use factor, T is the occupancy factor, d is the distance between the focus of the tube and the area to be protected, y H_w is the weekly dose limit on the other side of the armour (in mSv/week).

Although lower values were calculated, 1.5 mm thick lead was considered as a minimum shield since a safety factor of 1.5 was applied. Due to the suitability for the thickness and mechanical characteristics of the floor and ceiling, these were excluded from the study.

Table 1. Description of the proposed shielding systems analysed

Case	Shielding material	Description of layers	Amount (kg)	Constructive detail
#1	Lead (EN 12588:2006)	A) External hollow brick wall.	126.01	
		B) Lead sheet.	17.01	
		C) Support system made up of wooden battens.	1.84	
		D) Internal hollow brick wall.	72.01	
		E) Gypsum plaster.	10.00	
		F) Epoxy paint coat.	0.05	
#2	Clay brick [11]	A) Hollow brick wall.	353,70	
		B) Gypsum plaster.	10.00	
		C) Epoxy paint coat.	0.05	
#3	Rolled Steel [11]	A) External hollow brick wall.	126.01	
		B) Steel sheet.	183.09	
		C) Support system made up of wooden battens.	1.84	
		D) Internal hollow brick wall.	72.01	
		E) Gypsum plaster.	10.00	
		F) Epoxy paint coat.	0.05	
#4	Reinforced concrete [11]	A) Reinforced concrete wall.	365.10	
		B) Gypsum plaster.	10.00	
		C) Epoxy paint coat.	0.05	
#5	Barite concrete [11]	A) Barite concrete wall.	365.10	
		B) Gypsum plaster.	10.00	
		C) Epoxy paint coat.	0.05	
#6	Sprayed concrete (EN 14487-1:2005)	A) Hollow brick wall.	126.01	
		B) Reinforced concrete wall.	17.01	
		C) Gypsum plaster.	10.00	
		D) Epoxy paint coat.	0.05	
#7	Barite plasterboard (EN 520:2004 + A1:2009)	A) Hollow brick wall.	72.01	
		B) Support system made up of metallic steel profiles.	10.27	
		C) Barite plaster double panel system.	80	
		D) Epoxy paint coat.	0.05	
#8	Leaded plasterboard (EN 520:2004 + A1:2009)	A) Hollow brick wall.	72.01	
		B) Support system made up of metallic steel profiles.	10.27	
		C) Rock wool.	9.84	
		D) Leaded plasterboard	26.82	
		E) Epoxy paint coat.	0.05	

*(Measurements expressed in mm)

Following life cycle stages of each armour system, for each functional unit an inventory of materials and machinery involved in the processes of the scope was made using the Ecoinvent 3.1 database [58]. The transport of the material from the factory to a hospital using EURO3 trucks that travel the distances of Table 2 was considered. According to the cradle-to-grave approach, the energy consumed on-site construction activities for placing each system in the radiology room itself and the electrical energy for lifting construction materials using a 1.6 kW hoist according to the manufacturer's datasheet were considered. At the end of their useful life, it was estimated that machines would be used to dismantle the walls and transport 25 km to a waste disposal point using 16-32 metric ton EURO3 lorry.

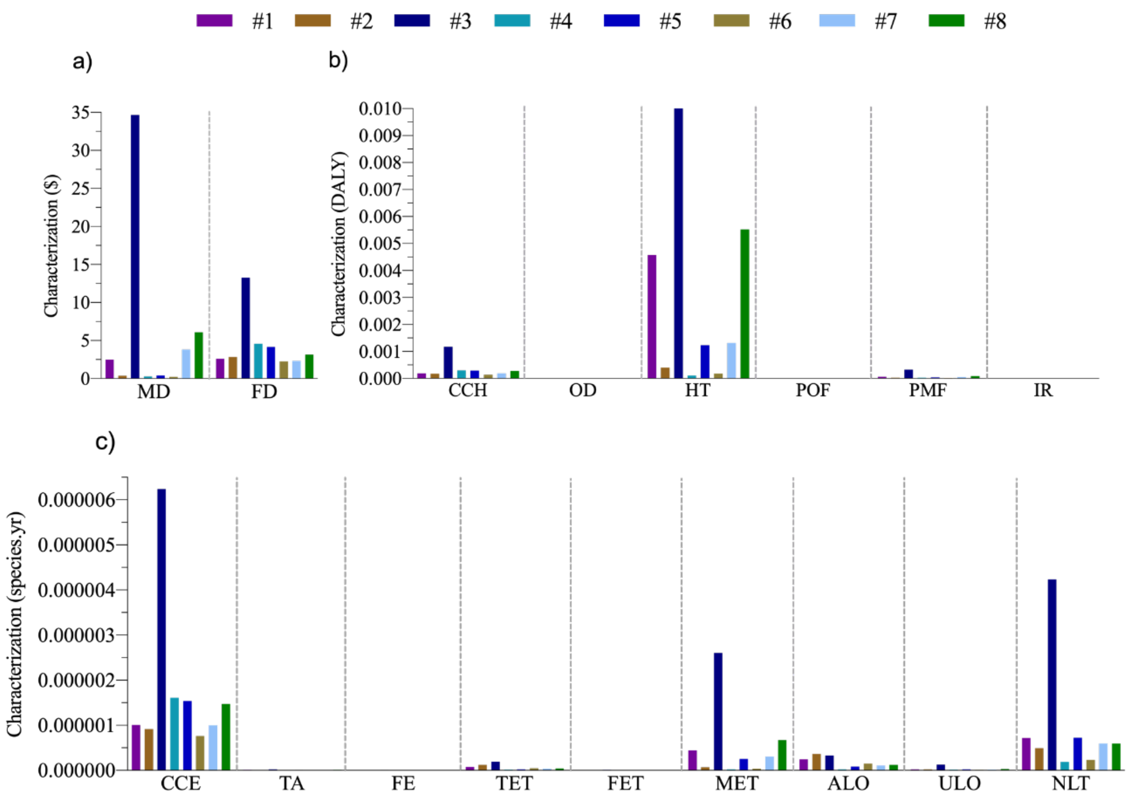
Table 2. Building materials inventory

Materials	Density (kg/m^3)	Distance (km)
Lead sheet	11,000	600
Wooden batten	500	200
Epoxy paint	1,000	600
Clay brick	1,600	200
Gypsum plaster	1,000	200
Rolled steel	7,800	600
Concrete	2,400	200
Barite concrete	3,200	200
Barite plasterboard	1,440	200
Leaded plasterboard	784 + 11,000	600
Rock wool	160	200

4 Results

4.1 General results

Fig. 5 shows the characterization of the impact categories. The most unfavourable impact category of the DALY set is human toxicity, in which systems #1, #3 and #8 stand out, with shield #3 being the one with the greatest impact (0.001 DALY). In the ecosystems quality set, system #3 is again the most undesirable, generating greater impacts in the categories climate change ecosystems ($6 \cdot 10^{-6}$ species·yr), marine ecotoxicity ($2.6 \cdot 10^{-6}$ species·yr) and natural land transformation ($4.2 \cdot 10^{-6}$ species·yr). Finally, for resources scarcity characterization, system #3 is again the most unwanted, presenting the highest score in the metal depletion category (34.6 $).

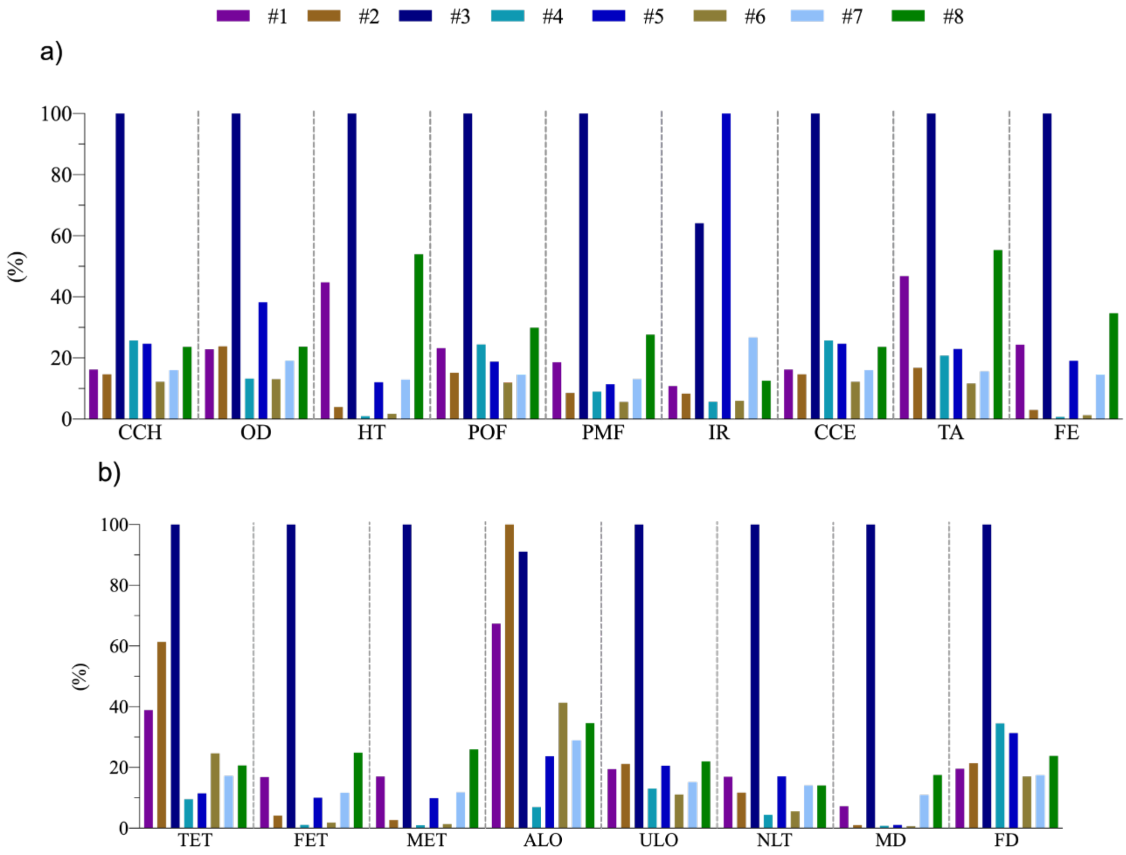


Climate change human health (CCH)
Ozone depletion (OD)
Human toxicity (HT)
Photochermical oxidant formation (POF)
Particulate matter formation (PMF)
Ionizing radiation (IR)
Climate change ecosystems (CCE)
Terrestrial acidification (TA)
Freshwater eutrophication (FE)
Terrestrial ecotoxicity (TET)
Freshwater ecotoxicity (FET)
Marine ecostoxicity (MET)
Agricultural land occupation (ALO)
Urban land occupation (ULO)
Natural land transformation (NLT)
Metal depletion (MD)
Fossil depletion (FD)

Fig. 5. Characterization of impact categories.

The characterization of impact categories of the shielding systems after the internal normalization process is shown in Fig. 6. An internal normalisation process was carried out whereby 100% was assigned to the system with the highest score in a category. Based on this re-scaling, the proportion of the impact on the rest of the systems is established.

Analysing by impact categories, design #3 presents the maximum values in all impact categories except ionizing radiation and agricultural land occupation, where the maximum values are obtained by systems #5 and #2, respectively. In general, all systems present similar values of relative importance in each impact category. However, the second most important is #5 in ozone depletion category, #8 in human toxicity and in terrestrial acidification. In terrestrial ecotoxicity, system #2 is relatively important, and in this and in agricultural land occupation systems #1, #2 and #3 stand out.



Climate change human health (CCH)
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Freshwater ecotoxicity (FET)
Marine ecostoxicity (MET)
Agricultural land occupation (ALO)
Urban land occupation (ULO)
Natural land transformation (NLT)
Metal depletion (MD)
Fossil depletion (FD)

Fig. 6. Internally standardized characterization of intermediate impact categories

4.2 Results according to midpoint approach

Single score results for different systems are reflected in Fig. 7 for midpoint categories. For all the designs analysed, human toxicity category has the highest values.

Solution #3 stands out as the most harmful to the environment considering all categories. The most important categories are, in order: metal depletion (22.47 pt.), climate change human health (11.38 pt.), climate change ecosystems (9.08 pt.), fossil depletion (8.6 pt.) and finally, natural land transformation (6.17 pt.).

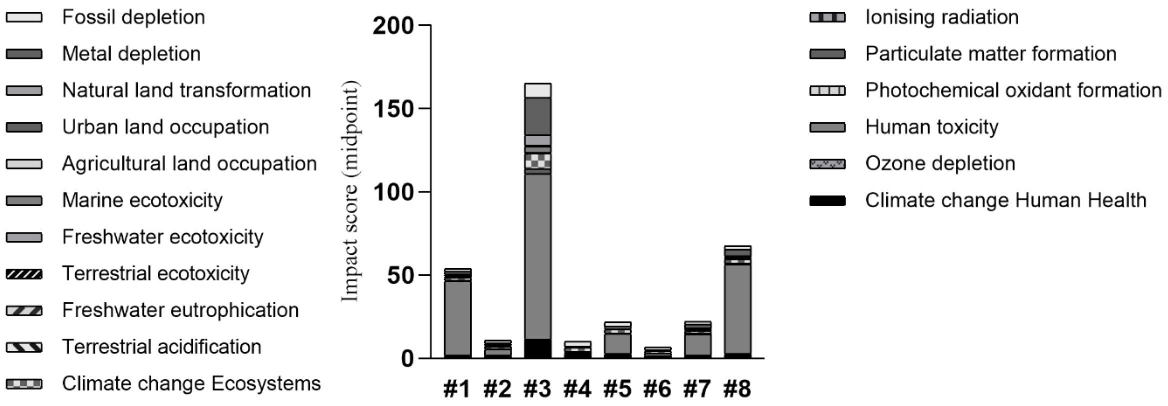

Fig. 7. Impact analysis - unique midpoint score.

4.3 *Results according to endpoint approach*

Fig. 8 shows the damage assessment by protection areas as an intermediate step to obtain the single score in the endpoint approach. With respect to damage to people's health, system #3 (0.012 DALY) is 3.5 times higher than the average ($2.2 \cdot 10^{-3}$) of the other seven designs. It is followed by system #8 with $5.9 \cdot 10^{-3}$ DALY and thirdly by system #1 with $4.8 \cdot 10^{-}3$ DALY. In the ecosystem quality damage path, case #3 ($1.4 \cdot 10^{-5}$ species·yr) is 3.8 times higher than the average of the remaining cases ($2.2 \cdot 10^{-6}$). The other systems have a very similar value. Finally, shield #3 (48.0 $) has the most serious impact on resource scarcity, being 4.6 times higher than the average of the other systems (5.1 ± 2.0 $). As in the previous protection area, the other designs have a similar impact.

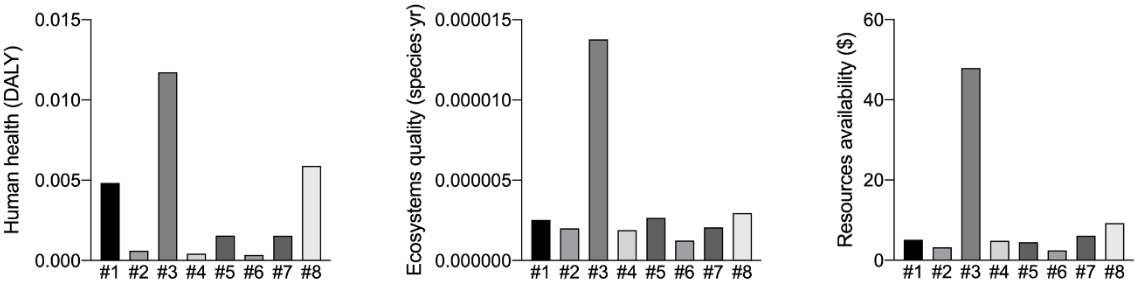

Fig. 8. Damage assessment by protection areas.

After normalizing and weighting the characterization factors, Fig. 9 shows the results of the unique endpoint score of each protection system. In this way, it is possible to compare the systems by aggregating the impacts on the protection areas. The most unfavourable shield system is that corresponding to steel, since it has an impact of 165.12 points/m^2 of X-ray room shielding, of which 113.99 are attributed to human health (69%), 20.07 to ecosystems (12.2%) and 31.06 to resources scarcity (18.8%). System #6 yields the most desirable data on environmental impact with 6.739 points/m^2 of X-ray room shielding, of which 49.3% are human health, 27.0% ecosystems, and 23.7% resources. According Fig. 5, the endpoint's single score result makes sense, since for the midpoint the human toxicity value is much higher than the other impact categories.

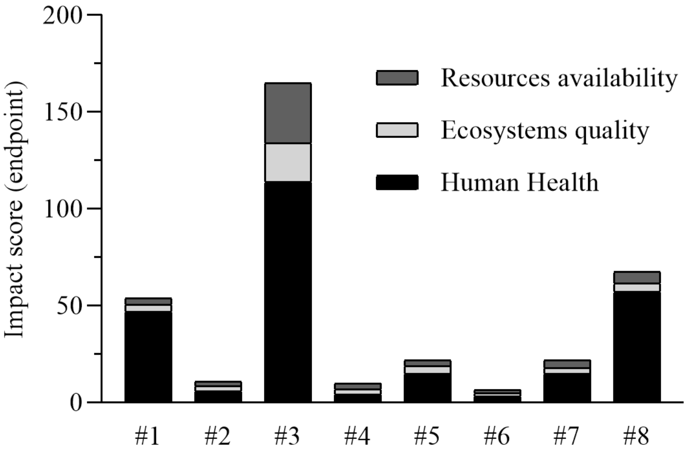

Fig. 9. Impact analysis - unique endpoint score.

4.4 *Unit cost and working time*

Fig. 10 shows the unit price and working time per functional unit considered. With respect to cost, on the one hand, design #8 presents the highest unit price (260.68 €/m^2), which is 1.88 times the following: system #1 of 138.16 €/m^2. On the other hand, system #2 has the lowest installation cost (37.90 €/m^2) and then there is system #4. With respect to execution time, system #2 (1.12 h/m^2) is the fastest in execution and systems #1 and #3 are the slowest (3.44 h/m^2). System #2 minimizes both dimensions (cost and time) with 37.90 €/m^2 and 1.12 h/m^2.

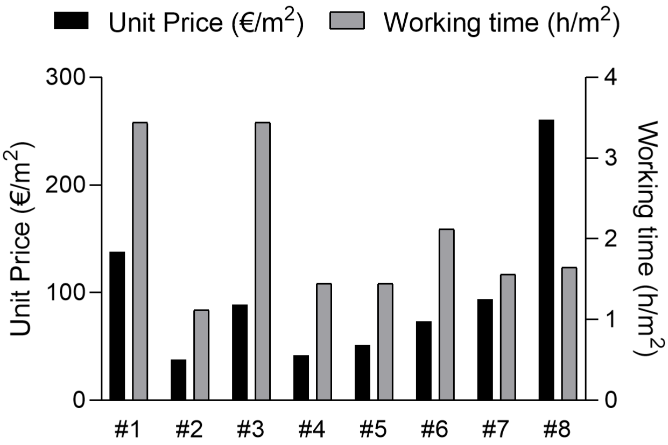

Fig. 10. Unit price and working time for the installation of the shielding functional unit.

5 Discussion

The above results demonstrate that a correct choice of anti-X shielding systems can significantly decrease the overall environmental impact embedded in a healthcare building, thus increasing its sustainability. On the other hand, Life Cycle Analysis is a suitable tool, which should be integrated into your design process.

The results obtained allow the selection of the system that generates the least environmental impact. To facilitate the understanding of the results, Table 3 shows the relative values of the endpoints, the main midpoints, the construction cost, and the labor required for the construction of the shielding systems analyzed. For this purpose, the most unfavorable reference value has been marked as the benchmark, so that the values obtained indicate how much more favorable a system is with respect to the reference value.

Table 3. Comparison of the shielding systems analyzed

			#1	#2	#3	#4	#5	#6	#7	#8
Constructability	Unit Price	Classification	M	L	M	L	L	L	M	H
		Weight	47,00%	85,46%	47,00%	83,91%	80,20%	71,77%	64,00%	0,00%
	Working Time	Classification	H	L	H	L	L	M	L	L
		Weight	0,00%	67,44%	0,00%	57,85%	57,85%	38,37%	54,65%	52,03%
Endpoints	Resources availability	Classification	L	L	H	L	L	L	L	L
		Weight	89,35%	93,34%	0,00%	89,86%	90,54%	94,85%	87,25%	80,69%
	Ecosystems quality	Classification	L	L	H	L	L	L	L	L
		Weight	81,61%	85,50%	0,00%	86,30%	80,67%	90,93%	85,00%	78,53%
	Human Health	Classification	M	L	H	L	L	L	L	M
		Weight	58,81%	94,83%	0,00%	96,31%	86,73%	97,09%	86,81%	49,78%
Midpoints	Climate Change Human Health	Classification	L	L	H	L	L	L	L	L
		Weight	83,83%	85,24%	0,00%	74,17%	75,40%	87,79%	84,01%	76,54%
	Human Toxicity	Classification	M	L	H	L	L	L	L	M
		Weight	55,23%	96,04%	0,00%	99,00%	87,97%	98,24%	87,13%	46,00%
	Climate Change Ecosystems	Classification	L	L	H	L	L	L	L	L
		Weight	83,81%	85,35%	0,00%	74,23%	75,33%	87,78%	84,03%	76,32%
	Metal Depletion	Classification	L	L	H	L	L	L	L	L
		Weight	92,75%	98,93%	0,00%	99,15%	98,89%	99,38%	89,05%	82,47%
	Fossil Depletion	Classification	L	L	H	M	L	L	L	L
		Weight	80,47%	78,60%	0,00%	65,58%	68,72%	83,02%	82,56%	76,16%

* **H: high; M: middle; L: low**

Thus, from Table 3 it can be inferred, for example, that the shielding system 3 is the one with the worst values from an environmental point of view, although the construction price is 47% lower than that of type #8.

The ceramic brick system (#2) shows the best environmental results. A compact surface must be guaranteed to ensure radiopacity. This implies that grooves in the direction of the x-ray towards the outside cannot exist and a mortar of the same density must be used. The main disadvantage of this construction material in the possible generation of cracks [59], particularly in areas with possible seismic movement. Another added problem is that this system takes up more usable space in the building, due to its thickness (18 cm versus 11 cm of the solution that takes up less space). Notwithstanding the above, the time and cost of execution is the lowest of all those analysed.

The reinforced concrete design (#4), a thickness of 15 cm is required to achieve similarity to its lead equivalent and, consequently, the high amount of material penalizes its environmental assessment. It is a viable solution for new construction projects. However, the placement of the formwork makes it difficult for renovation projects. As with the brick system, X-ray leakage through the setting joint must be avoided, as well as air occlusion. This solution has the second lowest cost, 84% less than #8 and installation time, 58% less than #1 and #3.

An alternative solution to the cast-in-place reinforced concrete construction system is the sprayed concrete system (#6). Shotcrete solves problems of both useful surface occupation (less thickness is required) and on-site execution (no formwork is necessary). A disadvantage during execution is related to quality control, so the evaluation of the thickness achieved requires specialized equipment (layer thickness measurement) to ensure radiopacity [60]. Unit both execution time and cost are higher than the previous two (clay brick and reinforced concrete). Nevertheless, these values are among the lowest of the proposed systems. In this case, the setting joint takes on special importance to avoid radiation leaks.

The rolled steel system (#3) reaches the worst environmental indicators. This statement appears to be unintuitive, because the toxicity of lead is greater than that of steel. However, it takes 9.7 times the amount of steel (system #3) compared to the amount of lead (system #1). In addition, the steel making process demands a much higher amount of energy compared to lead rolling. Lastly, execution time is the highest with the lead-based system, although the unit price is 47% lower than the most expensive (system #8).

The next least desirable system according to sustainability criteria is leaded plasterboard (#8). Its low environmental rating is compounded by its high installation cost, although installation time is among the lowest. The toxicity of lead is a determining factor in the assessment of this proposal. Analysing together systems #1 (lead based), #7 (barite plasterboard) and #5 (barite concrete) it can be inferred that lead is the culprit of the high environmental impact of system #8. The presence of barite in the systems (#7 and #8) increases the environmental impact since it is a heavy metal additive [61], concluding that plasterboard is not so harmful. Previous studies published about the environmental impact of barite show that this material as one of the least harmful to people, ecosystems and resources and, furthermore, it has adequate shielding properties [62]. When barite is used together with another material, the wall thickness required, and the execution time are very similar whether it is used with concrete (#5) or mixed with plasterboard (#7). However, its use as an additive to plasterboard presents an execution cost almost double that of barite concrete. In this sense, the mechanical and radiation protection properties of concrete reinforced with Boron and Basalt fibres are being characterized [63].

Lead (#1) ranks as the third least planet friendly. It is the most common system in these constructions; however, other options present a better ecological performance. In this sense, special-purpose lead-free shielding materials are emerging [64]. There is even the possibility of transparent shielding without this element for X-ray rooms [65]. Even so, for ceiling and floor shielding of rooms it is a very suitable material due to its low thickness. In any case, lead sheets should overlap at least twice their thickness to avoid leaks [11].

On the other hand, it should be noted that due to its high malleability and high density, lead has been found to be the most suitable material for anti-radiation shielding of doors and windows. Therefore, its use is recommended. However, to ensure operational safety, periodic inspections should be carried out to check the correct arrangement, especially of the door seals and door closures, which suffer a high degree of deterioration due to accidental impacts with wheelchairs and litters.

Whatever the system chosen, the shielding of the radio-diagnostic rooms must be constructed in such a way that the protection is not weakened by joints, ducts, pipes, etc., passing through the barriers, or different service elements embedded in the barriers. Moreover, observation doors and windows require special consideration to ensure adequate protection without impairing operational efficiency.

Direct access to a radiology room should be through a door with a plumb line. When the door is being opened, the sheet should protect the person opening it from exposure to radiation and give operating personnel time to warn them. The opening should be located on a secondary barrier, where the required shielding thicknesses are less.

Manufacturers tend to design diagnostic radiography equipment with less aggressive technologies for patients, which with lower radiation dose generate images with equivalent quality; and thus, lower shielding will be necessary in the future. The appearance of new diagnostic equipment and the replacement of obsolete ones require that it is usual to carry out reform works in this type of rooms to adapt them to new needs; therefore, it is necessary to take into account at the time of choosing the materials the impact that the reform generates in the environmental biosafety of hospitals [66]. In this sense, solutions that generate little dust and/or noise are usually recommended.

On the other hand, all materials to be used in the healthcare buildings construction process should be labeled to facilitate the determination of their environmental impact. This environmental labeling should include at least the greenhouse gas emissions and embodied energy per unit.

In any case, the characteristics of an X-ray installation and availability of resources and space will condition the type of shielding required. This work will help architects, engineers and infrastructure managers to select the most appropriate construction system, considering the perspective of sustainability taking into account the importance of passive elements [67].

This work is framed within the healthcare engineering discipline. Figure 11 shows an outline of the main subjects of this discipline according to Chu et al [68]. The work contributes to the green design of hospital facilities, which is within the design of healthcare infrastructures.

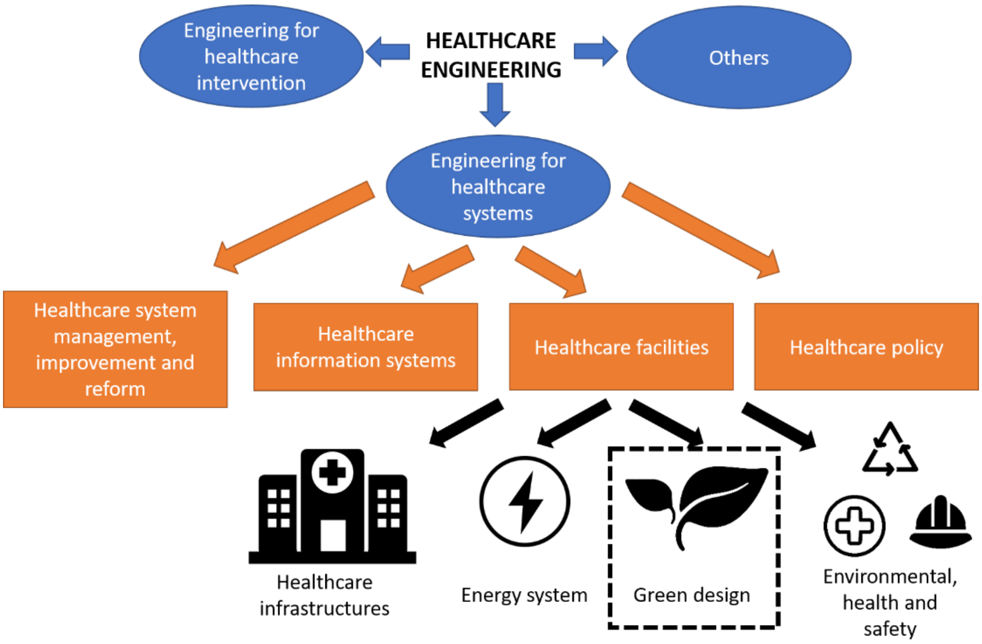

Figure 11. Framing of the work within the discipline of health engineering. Source: Own elaboration based on [68] . Iconcredtis: www.onlinewebfonts/icon CC BY 3.0

This work contributes to the achievement of the Sustainable Development Goals. The use of Life Cycle Analysis tools contributes to the sustainability of the construction sector and thus to the fulfilment of the SDGs in the field of engineering projects [69]. More broadly, research is also needed to determine the environmental impact of electromedical equipment due to its intense technological load one the road towards infrastructure resilience [70]. Obviously, that equipment will be chosen mainly considering the technical specifications required by medical procedures. Besides, the environmental variable must also be incorporated in the decision-making process for equipment acquisition, which contributes to improve the overall performance of hospitals [71].

The main limitation of this study is that is focused on medical diagnostic imaging equipment using X-type ionizing radiation. However, it is perfectly applicable to equipment of similar technology applied in veterinary medicine, materials analysis, quality control in infrastructures, among others.

Future works should be directed, on the one hand, towards the environmental evaluation of shielding of equipment that generates alpha, beta and/or gamma radiation emissions (i.e. linear particle accelerators) and, on the other hand, towards the modelling of these shielding systems using Building Information Modelling (BIM) technology, leveraging the connection between BIM, LCA and Life Cycle Cost (LCC).

6 Conclusions

A multi-case LCA analysis followed a bottom-up methodology based on main standards within cradle-to-grave perspective applying ReCiPe method was carried out for assessing environmental impact of various shielding systems for X-ray room in a hospital. Furthermore, a unit estimate of both execution time and cost based on specialised databases of construction complemented the information for decision making.

The findings of this study suggest that LCA is a suitable tool for designing X-ray rooms. As far as we know, the analysis of the life cycle of these installations had not been carried out before and constitutes a novelty of the work. This methodology allows the selection of the most adequate shielding system for walls, quantifying the environmental impact generated during its life span. In this way, it is possible to minimize the total environmental impact of a healthcare building.

The results of this study indicate that solutions with clay brick (#2), cast-in-place reinforced concrete (#4) and sprayed concrete (#6) are the most favourable in the different environmental impact categories analysed. In terms of execution time and cost, solutions with clay brick (#2), cast-in-place reinforced concrete (#4) and barite concrete (#5) are the most recommended System #6 is the most environmentally friendly, 1.6 times less than the next one (which is #4), although its unit price is 1.94 times the cheapest (which is #2) and its execution time is 1.89 times the lowest (which is #2 again). In the field of engineering, decisions are usually made using economic criteria and ease of execution, this work allows the incorporation of sustainability and environmental care in decision making.

This study permits to determine the most desirable alternative from an environmental perspective, based on endpoint indicators: human health, ecosystems quality and resources scarcity. The most favourable systems are clay brick (#2), concrete (#4) and sprayed concrete (#6) and the most unfavourable is steel (#3), followed by lead-based armour (#1). The system with the least environmental impact is shotcrete (#6), with a total of 6.739 points/m^2, while the steel armour is the most unfavourable system in terms of environmental impact with 165.12 points/m^2. The damage on human health occupies between 41% and 87% of the impact of the protection areas.

Therefore, from an environmental point of view, in a new construction project, it is recommended to use concrete, clay brick and sprayed concrete shields, since they are the less harmful construction systems because they have a lower impact. The choice of one or the other will be determined by other factors such as the useful space available or the availability of materials.

The findings of this study have several practical implications for future practice. This information can be used to develop targeted interventions aimed at choosing the system of isolation, which impacts on social, environmental, and economic benefit (three dimensions of sustainability). The knowledge generated in this study will assist in making investment decisions for Health Systems planning departments.

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