LCA AS A TOOL FOR THE ENVIRONMENTAL ASSESSMENT OF A PRE-CAST CONCRETE SHED

Part 1: Input data inventory analysis

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Abstract

Concrete (with an estimated consumption of 6 billion tons per year) is considered the most world-wide construction material used. Since 1990 the concept of sustainability was applied, also, to the buildings and construction sector ("Sustainable Construction"), being one of the most important economic sectors all over the world but, at the same time, one of the most pollutant emitting and resource demanding. This study focuses on the analysis of all the main input inventory data used for assessing the environmental impacts linked to the life cycle of a pre-cast concrete shed: great importance was given to the use of on-site collected specific data which was carefully verified for assuring its quality and reliability. The study was conducted in accordance with the ISO standards 14040 and 14044 (2006), with the aim of qualifying and quantifying the resources, the materials and the energy demand for the shed construction, use and end of life phases. Representative life cycle inventories are essential for any good quality life cycle assessment, being the fundamental building blocks for compiling reliable life cycle assessment studies.

Key words: buildings, precast reinforced concrete, environmental hotspots, functional unit, life cycle assessment

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1. Introduction

In the field of buildings and construction, efforts are being done for increasing energy efficiency by improving the performance of the building envelope through insulation and, also, for resorting, as much as possible, to the use of renewable energy sources. The energy-efficiency-building strategy, however, loses appeal if environmental aspects are not considered and assessed using appropriate tools such as Life Cycle Assessment (LCA) methodology through scientific and quantitative impact indicators, codified and defined at an international level. According to Flower and Sanjayan [1], lots of major owners are, nowdays, requiring their infrastructures to be designed with an Environmentally Sustainable Design (ESD) approach, thereby allowing for the increase of concrete environmental impact issues. From the early stages of a building design, it is necessary, in fact, to opt for appropriate technical solutions and materials so as to be able to reduce the environmental impacts linked not only to the construction phase but, most of all, to the life cycle of a building. In this context, LCA can be used so that the architectural design can be oriented to environmental sustainable and energy efficient buildings. Over the years, lots of researchers have dealt with the theme of building eco-sustainability and energy efficiency, developing high quality studies with relevant results. For instance, one of the first studies was developed by Jonsson et al. [2], regarding the use of LCA as a tool for comparing the effects on the environment of seven concrete and steel building frames representing the building technology in Sweden of that time. Other comparative analyses were developed by: Marceau and VanGeem [3], who applied this methodology for assessing (from an environmental point of view) a single-family house modelled with two types of exterior walls (wood framed and insulating concrete form) in five cities representing a range of U.S. climate; Passer et al. [4] who compared structural steelwork with other construction techniques; Zabalza Bribrián et al. [5], presenting the results of a comparative assessment of the most commonly used building materials with some eco-materials using three different impact categories; and Garcia-Rey and Yepes [6], assessessing LCA applicability on concrete structures so that construction's environmental performance can be improved. Finally, Josa et al. [7] presented a Life Cycle Impact Assessment (LCIA) comparative analysis of different inventories for EU cements. Regarding the application of LCA as a tool for environmentally improving building construction technology, the research brief, developed by Guiyuan and Srebric [8], presents and discusses four different LCA tools highlighting similarities and differences when applied to LCA. Similarly, Tuna Taygun and Balanh [9] analysed some models for improving the use of LCA in the fields of buildings construction and building products manufacturing. In addition to these studies, Kotaji et al [10] developed a report for contributing to the comparison and harmonization of different assessment tools and to the movement toward greener construction. It is, also, important to mention the work developed by Khasreen et al. [11], who reviewed the LCA methodology from a buildings perspective, highlighting the need for its use within the building sector and the importance of LCA as a decision making support tool. Furthermore, they reviewed some of the life-cycle studies applied to buildings or building materials and component combinations done in the period 1995-2007 in Europe and the United States. It is known that most of the impacts associated with a building life cycle are due to the energy consumption and, in turn, to fossil fuels depletion and carbon dioxide (CO2) emissions. In this context, Xianzheng et al. [12] developed a study regarding the application of LCA for assessing the life cycle of residential buildings in terms of energy consumption and CO2 emission. Focusing the attention just on pre-cast reinforced concrete buildings, the following studies are worth to be mentioned since believed more connected to the present research: López-Mesa et al. [13], in which LCA is used as a tool of environmental comparison between pre-cast with cast-in-situ concrete in floors construction for buildings; Dattilo et al. [14], who applied LCA to compare two single-storey buildings made of reinforced concrete using two different construction technologies: precast and cast in situ; The Canadian Precast/Pre-stressed Concrete Institute [15] for environmentally assessing precast concrete commercial buildings in two different locations of Canada: Toronto and Vancouver; Baldwin et al [16], developing a study for modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings, thereby allowing for reducing the environmental impacts linked to the construction field.

It can be observed that just a very few studies concern the environmental assessment of concrete structures. It is in this regard that this article discusses the input-data inventory analysis of a precast reinforced concrete shed, providing a fundamental building block for compiling a full LCA study.

The study is the result of a collaboration between the Research Centre ENEA (National Agency for new techniques, Energy and Environment) of Bologna (Italy) and a Firm, located in the province of Catania (Italy), which supplied all data needed for developing the inventory analysis.

2. Material and methods

LCA methodology is based on the requirements of the ISO standards 14040:2006 [17] and 14044:2006 [18] and is characterized by the framework reported in Fig. 1.

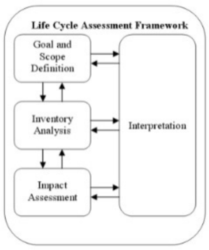

Fig. 1 Life Cycle Assessment (LCA) main phases

This study deals with only the first two steps of LCA, with the aim of developing the inventory analysis of a pre-cast reinforced-concrete shed, taking into account the main input inventory data. The output flows, in terms of primary resources used and substances emitted in air, water and soil, since not directly available at this step, are going to be obtained after loading the input data into the 7.3.3 version SimaPro [19], accessing the Ecoinvent v.2.2 database [20], and then processing them using an appropriate calculation method. The phases of Life Cycle Impact Assessment, Interpretation and Improvement will be object, in fact, of a further paper where only the output flows mostly weighing on the total damage are going to be presented and discussed.

2.1 Goal and scope definition

The goal of an LCA must state, unambiguously, what the intended application, the motivation to conduct the study and the type of audience that is targeted are [21].

According to this, the present paper aims at investigating the Life Cycle Inventory (LCI) of a pre-cast concrete shed devoted to the storage of non-perishable goods (no offices inside) and identifying the input material and the energy flow inventories associated with its life cycle. In this context, the main goal is to provide as much as possible an exhaustive and extensive description of all the involved input flows and of the entire hypothesis made for the development of the study. For this reason, the entire paper is devoted to analysing and discussing just the LCI phase. This approach is not common in LCA-studies development and represents the peculiarity and originality of this paper, making it a reference for all the interested stakeholders and a valid building block for further environmental assessments.

The study was conducted for the purpose of pure scientific research and it is addressed to LCA practitioners, as well as to those people working in the buildings and construction field and, in particular, in the sector of the industrial buildings made from precast reinforced concrete. In this way it is possible to inform them about the main resources, materials, and energy to be used when developing a similar study, allowing them to realize further reliable LCA studies. Furthermore, thanks to the present study, the Firm will be able to better enter into the merits of the most inventory processes within the phases of the precast reinforced concrete artefacts manufacturing and assembly for the shed construction.

2.1.1 Functional unit (FU)

In order to calculate the “in - out material and energy flows”, a pre-cast concrete single - storey shed (55 years lifetime) was chosen as the FU. This shed has a net surface of about 1730 m^2 (the most common size manufactured by the Firm). It is 7.80 m high, 80.41 m long and 22.00 m wide and, as said before, it is devoted to the storage of non-perishable goods. The building is located in the province of Catania (Italy), whose data, in terms of climatic zone, altitude, outside winter temperature, day degrees, seasonal average temperature (just to name a few of them) were properly calculated and used for the energy analysis.

The shed is composed of: sixteen pillars and fourteen "H" formed section beams as load-bearing structures; eighty-one panels as side-walls; and seventeen "Ondal" teal and seventy-five curved precast concrete slabs for the shed roof covering.

2.1.1.1 Pre-cast concrete elements production and shed assembly

Pre-cast concrete structures are characterized by a typical production process: using cement, aggregates, sand, water and fluidizing additives, concrete is produced in the concrete mixing plant and, then, transferred to the production lines by means of little wagons travelling on overhead rail. In the particular case, the aggregates used are produced from basalt extraction and processing. After concrete is cast, it remains within the formworks for the time required for the concrete to reach the strength and setting required as per specification. After this stage, the precast concrete elements are transferred to a storage area waiting to be transported, by trailer truck, to the mounting yard. Here the shed is assembled: mineral wool, fiberglass curve slabs, cement-fibre curved slabs are mounted to provide shed roof insulation, sky-lighting and covering. Fixtures, heating/cooling, electric wiring and lighting are, then, attended to. A flow chart of the shed production process is shown in figure 2, reporting the main input data and manufacturing phases. The thicker arrows represent the transportation associated with the product, while the dotted lines indicate the processes not included in the system boundaries.

The roof skylights made from fiberglass are square-shaped with a length of 90 cm, width of 1 m and thickness of 5 mm. Additionally, the shed has sixteen windows on each of the two long sides. Each window (h:1.10 m x w:1.50 m) has a PVC frame and a 12 mm (air) inter-space double glazing with a visible area of 1.40 m^2. The shorter two sides have six windows, equally spaced and having the same dimensions and constructive characteristics of those placed on the long sides. In the light of their location in the shed side-walls, all windows are electrically operated.

The following items were, also, taken into account:

- three white painted steel service doors, made of low-alloyed steel, w1.30 m x h2.30 m (area = 2.99 m^2), on the longer sides, 5 mm thickness and weight of 108.33 kg (39.25 kg/m^2);
- two entry/exit openings on the longer sides and one on each of the two shorter sides. They have all the same height and width of 4.50 m and 4.75 m, respectively.

Considering the purpose of the shed, these dimensions allow for the entry and exit of the goods using loading and unloading vehicles; entrance/exit closure is done by electrically operated PVC shutters.

The thermal power plant, used for the warehouse heating and cooling: details are reported in the use phase section.

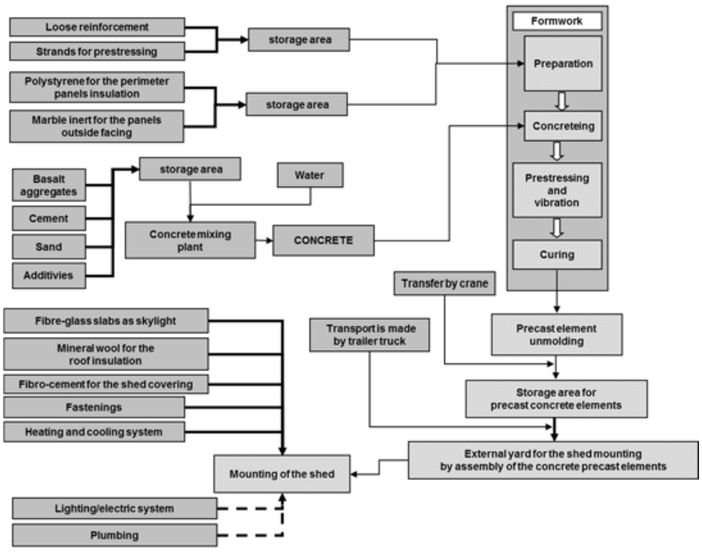

Fig. 2. Flow chart of the shed production process

2.1.2 System boundaries

As shown in Fig. 3, the chosen system boundaries included the phases of: *extraction and processing of the resources necessary for the pre-cast reinforced concrete artefacts production*; *the artefacts production*; *the shed mounting*; *the use of the shed*; and *its end of life*.

Regarding the operations preceding the shed mounting, those taken into account were the shed site preparation through land levelling and excavation and the cast-in-situ concrete works, such as the foundations and the construction of the ground floor including machinery use and fuels consumption. Direct emissions, linked to land preparation and excavation operations, were not considered, as well as the use of water for removing the particulates emitted.

Apart from the concrete mixing plant, that already exists in the Ecoinvent v.2.2 database and with respect to the main industrial machines used in the prefabrication sector (i.e. the formworks), it should be noted that: no similar machinery was found in Ecoinvent v.2.2; no specific data were found in scientific literature; it was not possible to collect on-site data and information from the formworks manufacturing Firm.

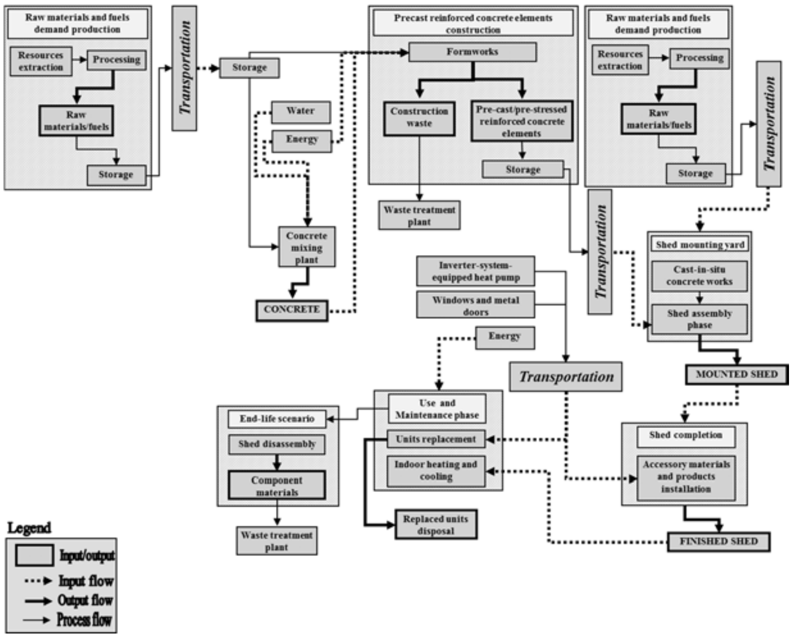

Fig. 3. The system boundary

For all these reasons, the formworks were excluded from the system boundaries, in terms of the share associated with the production of the precast concrete elements. The electrical energy consumption during the formworks operation phase is included in the Firm's overall energy consumption. The operations linked to precast reinforced concrete artefacts assembly, in terms of building equipment and support structures for the share associated to the building in question, were excluded from the system boundaries. This was done because of the absence of specific data and also because negligible environmental impacts were expected, resulting from considering their shelf life and the number of building structures they are used for. Fuels consumption for artefacts mounting was accounted for and used, because directly managed by the Firm: it was supplied in fact together with other information related to the shed construction and mounting. Furthermore, fixtures, in terms of production and supply, were included in the system boundaries, with exception of the electrically operated PVC shutters, since nothing was found in Ecoinvent v.2.2 and, at this step, no data from producers were available. The use of the shed was represented just considering indoor heating and cooling. It has to be underlined that this phase could have been excluded from the system boundaries, since the examined building is only used for the storage of non-perishable goods. Nevertheless, it was taken into account for assessing not only the energy performance of the shed, but also the environmental impacts due to these activities in comparison to the others characterizing the shed life cycle. The electric and lighting systems and the plumbing, in terms of production, installation, operation and maintenance, were not included because: on-site specific data were no available; no useful data were found in Ecoinvent v.2.2; and low inventory levels were expected. The energy consumption for windows opening and closing was considered included in the electric system operation and so not taken into account. The maintenance phase was represented just considering the replacement of windows, doors and thermal power plant, after the first installation and every time their shelf life has ended. Disposal of the replaced units and transportation to the treatment plant was considered as part of this phase and then accounted for.

Finally, as already said, the end of life phase was included in the analysed system, in terms of component materials treatment processes including all the involved transports. The shed disassembly phase, due to its complexity, was not accounted for because on-site specific data were not available.

2.2 Inventory analysis and data collection

The LCI analysis quantifies the use of resources and materials and the consumption of energy, as well as the involved transportations associated to a product life cycle [22]. As stated before, the study was done in accordance with the guidelines and requirements of the ISO 14040:2006 and ISO 14044:2006.

For this phase, since a particular specialised production system was assessed, great importance was given to using primary data, in other words specific data supplied by the Firm. The processes used for representing the consumption of resources, materials and energy, as well as the use of transport means, were extrapolated from Ecoinvent, because believed a reliable background data source. It should be noted, also, that the data collection was carried out accessing this database for verifying what processes and raw materials were missing since strictly linked to the specific manufacturing process. It was observed that not all the needed data were included in it, so it was necessary to represent them creating new items or making assumptions and hypothesis for using background data within the database. For major details, see Tables 1-6.

The data provided by the Firm were, mainly, about the techniques adopted and the materials used for the precast concrete artefacts production and assembly for the shed construction, except from the fixtures (windows and door) and the thermal power plant. For calculating the shed's summer and winter energy performances, the Firm provided data and technical information about the materials, the thickness and the thermal conductivity of the layers for the perimeter surface, the pavement and the cover. The shed windows were designed not only in accordance with the needs and requests of the shed owner but, also, for limiting, as much as possible, the thermal dispersions in winter. They were produced by a local Firm which was also instructed for their transportation to the shed assembly site and further installation.

All the related and useful data (window dimensions and technical characteristics) were provided for the development of the study and their life cycle was represented using what already within the Ecoinvent v.2.2 database appropriately adapted to the particular case. Regarding the metal doors, no primary data were collectable on site since no firm was available to provide them; for this reason, reliable average data were used and, then, appropriately managed for best using the Ecoinvent items. The thermal power plant was designed on the basis of the heat flows through the building envelope in winter and summer. In this case, average data were extrapolated from the Ecoinvent v.2.2 database. The primary winter energy and the heat entering the shed in summer were calculated applying the most common formulae on heat transmission and using a software produced by Italsoft Group [23]. Finally, due to the fact that the end of life of the shed is outside construction Firm's control forecasting and estimations were applied, choosing, for each component material, the most sustainable scenario compatibly with the data contained within Ecoinvent v.2.2

2.2.1 Concrete production phase

For this phase, 1 m^3 of concrete was chosen as FU, with the system boundaries going from the raw materials production and supply to their processing for the concrete production. In Table 1, the concrete production input data are shown. Inventories for the shed production life cycle were computed for the production of the shed using 377 m^3 of concrete.

2.2.2 Pre-cast concrete shed construction phase

This phase is concerned with the manufacturing of the pre-cast concrete elements (beams, pillars, panels, "Ondal" tiles) with the input data shown in Table 2. Land transformation from pasture and meadow to industrial area and occupation as construction site were accounted for. In addition, the data regarding the preliminary operations and the shed assembly are shown in Tables 3 and 4, respectively. Regarding the preliminary operations included within the system boundaries, the activities and works taken into account were: the land transformation from pasture and meadow to industrial area; the excavation of the land portions for the shed foundations by mean of hydraulic digger; and foundations and pavement.

Table 1 Inventory data concrete production

Functional Unit (F. U.)	**1**	m^3	Basalt-based concrete with 2500 kg/m^3 specific weight
Input flow	**Physic amount**	**Measure unit**	**Comment**
Raw materials and resources			
Tap water, at users	**200**	l	This process, taken from Ecoinvent v.2.2, using ground, river and lake water, considers the infrastructure and energy consumption for water treatment and transportation to the end user.
Portland cement	**0.425**	t	The Portland cement used has a 52.5 (CEM II) strength class and the following composition: clinker 91%, gypsum 6%, additional milling substances 3%.
Basalt gravel	**0.650**	t	This input material (basalt gravel) is used by the Firm (and also by most of the firms located on the Etna Volcano slopes), to give the concrete high strength. Furthermore, because the Firm site is close to the yards for basalt extraction from quarry and lava stone processing, this makes transportation less impacting. The basalt inert is peculiar of the Sicilian territory and it is not listed in the Ecoinvent v.2.2 database. For this reason, it was necessary to create the manufacturing process life cycle, starting from the basalt extraction from pit, also including lava stone

			crushing and then inert washing. This was done using the same process for limestone in the Ecoinvent v.2.2 database, replacing the item “Lime, at mine” with the one “Basalt, at mine”. In doing this, any eventual difference in the manufacturing process was considered negligible. The energy consumption for limestone crushing can be considered quite the same compared to the basalt one, since the hardness of the two stone-types is comparable. The Firm also owns a plant in an area of Sicily where lots of limestone quarries are present. For this reason, limestone aggregates are commonly used for prefabricated structures using the same mixture of the one when basalt is used. Their hardness is comparable to that of basalt, otherwise concrete strength would be compromised. Therefore, the use of the aggregate-type is only linked to the Firm geographical location based on economic and environmental issues.
Basalt sand	**1**	t	This sand is obtained by inert milling: sand is washed, too. A peculiarity of the Firm practice in producing concrete for prefabrication is to use both fine and course aggregates. In this case, we proceeded as done for the basalt inert. The process, named “Limestone, milled, loose, at plant”, taken from the Ecoinvent v.2.2 database, was used, replacing the item “Limestone, crushed, for mill” from the abovementioned database, with the process “basalt gravel” already created. Both basalt gravel and sand are supplied to the manufacturing plant in a bulk form.
Siliceous sand	**0.170**	t	
Limestone filler	**0.050**	t	
Acrylic additive for concretes	**5.25**	kg	The additive is used in order to ensure that the concrete flows better once casted inside the formwork
Electricity			
Electricity MV, use in Italy + import	**9.55**	kWh	This is referred to the consumption of electric energy associated to the functioning of the concrete mixing plant
Processing plants			
Concrete mixing plant	**1.67E-6**	p	This is the plant share for processing 1 m^3 of concrete. The calculation was developed considering that the amount of concrete produced in average every year is equal to 30000 m^3 and that the lifetime of the concrete mixing plant is 20 years. For representing such industrial machine, the Ecoinvent v.2.2 database has been accessed using the existing item "Concrete mixing plant".
Transports			
Cement	**25.5**	t*km	For all the raw materials, transportation is done by means of Euro 4, 28 t lorry. The alongside values were calculated multiplying the relative amount for the travelled distance; in particular: 60 km for cement; 25 km for basalt inert; 25 km for basalt sand; 35 km for siliceous sand; 300 km for limestone filler; 1500 km for acrylic additive for concretes.
Basalt inert	**16.25**		
Basalt sand	**25**		
Siliceous sand	**5.95**		
Limestone filler	**18**		
Acrylic additive for concretes	**7.875**		

Foundations are composed of sixteen plinths in reinforced concrete appropriately designed and formed (Fig.4). Pavement, having a surface of 1728.22 m^2 and a thickness of 20 cm, is made of concrete reinforced with electro-welded FeB44k steel grids composed of square-shaped meshes with side length of 15 cm and bar section of 8 mm.

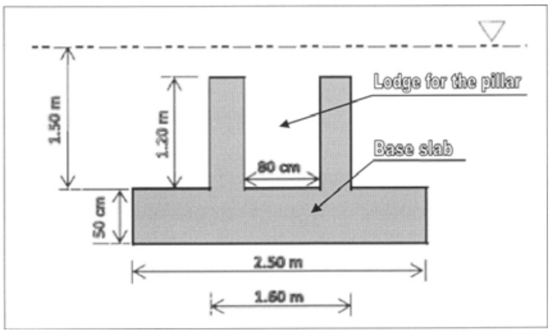

Fig. 4. Foundation plinth

The shed construction phase can be considered complete when all the precast concrete elements, after being transported to the shed site, are assembled.

Regarding the white painted steel service doors, their production was represented by appropriately combining data from Ecoinvent v.2.2 with average information provided by local Firms (Table 5). Furthermore, assuming that each door's shelf life is 30 years, in the light of the shed life time, one replacement was considered after doors are installed for the first time.

As shown in Table 5, the dataset used encompasses manufacturing processes to make a semi-manufactured product into a final product and also includes average values for the processing by machines, as well as the factory infrastructure and operation.

In order to represent the production process of the window, the PVC frame and the double glazing were taken into account: for both of them, the Ecoinvent v.2.2 database was used. In particular, in the first case, a plastic window frame with 1 m^2 visible area and 94.5 kg weigh is assumed to be the functional unit. The production process involves the use of raw materials, such as PVC polymer, steel and aluminium and energy consumption referred to the functional unit chosen. In addition to this, all the main typical processes, such as PVC injection moulding and extrusion, section bar rolling for steel fittings, section bar extrusion for aluminium parts, were accounted for. All the road transport at different production phases were also taken into account. With regard to the double glazing production, this refers to 1.06 m^2 glazing used for 1 m^2 of visible area. The FU is 1 m^2 double glazing with a 20 kg weigh. Raw materials transportation, waste water and glass waste, as well as the relative end-scenario treatments, were taken into account. For the window manufacturing, no other processes and raw materials were accounted for but the transportation of the assembly parts (PVC frame and double glazing) to the window manufacturing plant: the FU considered corresponds to 1 m^2 of window finished-product. This was used as input material in the shed assembly process, considering that, in the particular case, each window has a 1.65 m^2 overall area and weights 185.60 kg (plastic frame + double glazing) corresponding to 112.45 kg/m^2. Once manufactured, the window is transported (d= 25 km) to the shed assembly yard. As done for the metal doors, even in this case the windows' shelf life was taken into account, a lifetime of 20 years: this means that, in the shed's life-time, they are replaced two times after the first installation.

2.2.3 Shed use phase

This phase is, mainly, about the primary energy consumption due to the use of the thermal system during the whole lifetime (55 years) of the shed. The thermal analysis was done calculating first the heat flows through the building envelope both for winter and summer seasons and, then, designing the heat pump, with air-conditioner function.

It was found that in winter, primary thermal energy requirement is 170,467 MJ/year: converting such value into kWh and dividing it for the plant performance coefficient (3.5), the electric energy consumption for the heating phase is equal to 13,539.95 kWh per year. Considering that a thermal power plant has an average lifetime of ten years and the working time is 8 hours a day, 30 days a month, 4 months a year, the required plant nominal power is 14.66 kW.

In fact, the energy analysis cannot be separated from the study of the behaviour of the building during summer. During this period, for the indoor cooling, the thermal plant absorbs primary energy, in the form of heat, equal to 235,648.37 MJ/year. The equivalent in kWh/year, considering a refrigeration coefficient of 2.5, is 26,204.098 kWh/year. The nominal power was found to be 28.37 kW. Comparing the two values of nominal power for the shed indoor heating and cooling phases, it was decided to take in consideration the highest one. In order to modulate the thermal load, for guarantying the winter energy demand with low electricity consumption and low heat waste values, a model of thermal power plant, equipped with an inverter system, was chosen. The plant in question has a pick nominal power of 30 kW and the following dimensions: height: 0.65 m; length: 1.00 m; and width: 0.50 m. It is purchased from a local retailer (d= 40 km from the assembly site); for the completeness of the study, the distance from the thermal power plant production site in Germany to the retailer was also considered. In both cases, road transportation was considered.

Table 2 Inventory data pre-cast concrete shed construction

Functional Unit (F. U.)	**1**	p	The functional unit as expressed alongside refers to a shed having the dimensions, airspace and surface footprint listed in Table 1 and an overall mass of 942.5 tons.
Input flow	**Physic amount**	**Measure unit**	**Comment**
			Resources
Water, process, well, in ground	**169650**	l	
Transformation from pasture and meadow	**32**	m^2	Firm yard has an area of 120,000 m^2, including input materials storage area, construction site, precast reinforced concrete artefacts storage area, canteen and offices. The value reported alongside was calculated hypothesizing that the Firm has a 50 years shelf-life and considering that about 75 sheds are annually produced on an average.
Transformation to industrial area	**32**	m^2	
Occupation, construction site	**32**	m^2a	
			Raw materials
Concrete	**377**	m^3	The concrete used is produced by the Firm within its construction yard processing all the raw materials listed in Table 2.
Marble inert from the North of Italy	**0.020**	t	Gravel is used for the precast concrete side-panels facing: it is placed on the formwork surface before the cast of concrete. Its origin was specified just for properly taking into account the transportation to the building construction Firm. The production technology is the same: from the extraction from the mine to the crushing process for the gravel production. Marble is formed through a process of metamorphic sedimentary rocks, such as dolomite, which causes a complete re-crystallization of calcium carbonate: this process gives rise to a mosaic of crystals of dolomite. For this reason, the production process of such inert was created modifying the one, already existing in the Ecoinvent v.2.2, named "Limestone, crushed for mill", by appropriately replacing Limestone with Dolomite. Considering that the item "Dolomite, at plant", in the abovementioned database, refers to 1 kg of milled dolomite stone, in the process "Limestone, crushed for mill", "Lime, at mine" it was substituted with "Dolomite in ground" adding the item "Mine, limestone" for well accounting the environmental impacts due to the quarry and to stone extraction, as well.
Marble inert from Sicily	**0.030**	t	
Steel brackets	**26**	t	The steel used is FeB 44 k and it is transported to the Firm in the form of coiled strands which are properly bent to form the brackets required. The bending machine was not taken into account; the electric energy demand for the process is included in the Firm energy overall consumption.
Electro-welded steel	**11**	t	The relative manufacturing process was represented considering the steel strands cutting and welding: each steel bar section has a diameter of 10 mm. A FeB44k type steel has been considered to be used. The FU is 1 m^2 shaped steel grid composed by 100 square-shape meshes with side length equal to 10 cm. In creating this process, a scrap of approximately 5% was taken in consideration: the value reported alongside refers to the real requirements. Raw-material transportation was included. The electro-welded steel grid is produced in another Firm and transported by trailer truck to the Firm producing the shed.
Steel strands for pre-stressing	**12**	t	For the pre-stressing phase, seven weaved wires bar are used; they are characterized by a section diameter equal to 12.5 mm. They guarantee a maximum elongation strain equal to 1860 MPa. For this raw material, high grade steel, provided by the Firm and taken from the Ecoinvent v.2.2 database, was used.
Polystyrene foam slab	**285**	kg	This is used for heat insulating the precast concrete panels composing the sidewalls: thickness is equal to 8 cm. The value alongside has been calculated multiplying the data of 19 m^3 (provided by the Firm) per the polystyrene density of 15 kg/m^3
Paint for side panels formworks	**1.88**	kg	Once applied on the formwork surface, it creates a sort of film with the main function of avoiding the contact between the formwork metal surface and the concrete. This is for protecting the formwork itself from rust phenomena and so guaranteeing its durability. For accounting the main environmental impacts, "Acrylic varnish, 87.5% in H_2O, at plant", reported by the Ecoinvent v.2.2 database, was used.
Lacquering oil	**51.94**	kg	It is applied on the abovementioned paint for causing the delay of the concrete setting and gives various effects.

Table 2 Inventory data pre-cast concrete shed construction (continues)

Input flow	**Physic amount**	**Measure unit**	**Comment**
		Raw materials	
Lubricating oil	**331.76**	kg	This oil is sprayed on the upper and lower formwork surfaces for facilitating the detachment of the precast concrete elements at the end of the curing phase. This is done for all the precast concrete elements, with exception for the side panels.
Fuel oil	**2564**	kg	The oil is burned in a boiler within the Firm yard for producing heat in the form of steam in the necessary amount for accelerating the curing of the concrete cast in the formwork. The value reported alongside, as most of the data used for the study development, was provided by the Firm and, for better taking into account the environmental impacts due to the combustion process; it was associated to the item "Light fuel oil burned in boiler 10 kW condensing, not-modulating" in the Ecoinvent v.2.2 database. Such item considers a production of heat equal to 42.7 MJ per kg of burned light fuel oil.
Diesel	**369**	l	A) This is for the vehicles operating inside the firm construction yard.
	753		B) This is the diesel requirements for the crane used in the assembly site for the lifting of each precast concrete element and so for the shed mounting.
	295		C) The alongside value refers to the use of vehicle equipped with platform and basket used for the workers lifting.
		Electricity	
Electricity MV, use in Italy + import	**10224.24**	kWh	The alongside value refers to the Firm overall energy consumption, appropriately related to the functional unit.
		Processing plants	
Formworks	**---**	kWh	See system boundaries paragraph
		Transports	
Concrete	**---**	t*km	For all the raw materials, transportation is realized by means of Euro 4, 28 t lorry. The alongside values were calculated by multiplying the relative amount for the travelled distance; in particular: - 160 km for the coiled steel strands for producing the brackets; - 35 km for the electro-welded steel grid; - 2000 km for steel strands for pre-stressing; - 300 km for marble inert from the most westerly tip of Sicily; - 1300 km for marble inert from the North of Italy; - 250 km for the polystyrene. The paint for side panels formworks, the lacquering oil, as well the lubricating one, are produced by the same Firm: their transportation is done by means of road transportation 1,500 km. In this case, transport is mainly Euro 4, 16 t lorry. Regarding diesel, the total amount required for the operations linked to the building construction by using the above listed means (A, B, C) is equal to 1105.26 kg, considering a density equal to 0.78 kg/l. The Firm is equipped with an internal filling station: transport is done every month about two and a half times by 5000 l tanker travelling for 60 km. Concrete is not transported since produced and used in site.
Coiled steel strands for brackets	**4160**		
Electro-welded steel	**385**		
Steel strands for pre-stressing	**24000**		
Marble inert from the North	**26**		
Marble inert from Sicily	**9**		
Polystyrene (expanded)	**71.25**		
Diesel	**66.315**		
Paint for side panels formworks	**2.82**		
Lacquering oil	**77.91**		
Lubricating oil	**497.64**		
Fuel oil	**153.84**		
Precast concrete elements	**14137.5**	t*km	In this particular case, the shed assembly site is located at a distance of 15 Km from the Firm construction yard. All the precast reinforced concrete elements composing the shed have an overall weigh of 942.5 tons. In this case, transport was represented with a lorry>32 t calculating the value reported alongside.
		Solid Waste	
Wood packaging	**13.195**	kg	
Lead batteries	**2.262**	kg	
Construction waste, unspecified	**50434**	kg	
Vehicles soaked filters	**2.64**	kg	
Retarding lacquer plastic packaging	**9.048**	kg	
Used oil	**8.29**	kg	

Table 3 Inventory data preliminary phase

Functional Unit (F. U.)	**1**	p	The functional unit refers to the preliminary operations, such as the excavation and cast-in-situ concrete works, associated to the shed object of the present study.
Input flow	**Physic amount**	**Measure unit**	**Comment**
Raw materials			
Ready-mixed concrete	**415**	m^3	For these works, concrete is produced by another Firm and then transported to the shed assembly site being ready for the cast. The concrete receipt is nearly the same than one adopted by the shed manufacturing Firm (see table 1).The alongside amount, equivalent to 1037.5 t, includes the requirement for the foundations and the pavement.
Steel reinforcement	**38**	t	
Main processes			
Excavation	**288**	m^3	The alongside value refers to the amount of soil resulting by the excavation process. A share of it is replaced once the concrete curing phase is ended and the foundations manufacturing is so complete. Another share is re-used for other unspecified purposes. The Ecoinvent v.2.2 database has been accessed using the item "hydraulic digger" which includes the raw materials, the resources and the energy requirements, as well as the main operations, for its manufacturing. Diesel consumption is included, because considered by the database, in the amount of 0.131 kg per m^3 of excavated soil. Lubricating oil is considered to be equal to 0.0025 kg per m^3 of excavated soil.
Transports			
Concrete	**31125.00**	t*km	The Firm producing the concrete for the cast-in-situ operations is 30 km far from the shed assembly yard.
Steel	**1140.00**		Steel is purchased at a Firm located at a distance of 25 km from the shed site.
Waste			
Soil waste	**288**	m^3	

Table 4 Inventory data shed assembly

Material	*Distance from the production site (Km)*	*Amount (t)*	*Input data (t*km)*
Mineral wool for the shed roof thermal insulation	**1200**	**0.778**	**933.24**
Cement-fiber slabs for the shed roof covering	**1200**	**27.65**	**33,181.2**
Fiberglass slabs as roof skylights	**30**	**0.273**	**8.19**
Windows	**25**	**8.165**	**204.125**
White painted steel service doors	**20**	**0.702**	**14.083**

Table 5 Inventory data steel doors production

Functional unit	1 m^2 of the type of door briefly described in the text		
System boundaries	From the raw materials production and supply by road transport to their processing for the door manufacturing		
Ecoivent v.2.2 database items	AMOUNT	UNIT	COMMENT
Steel product manufacturing, average metal working	**41.21**	kg	This value includes an additional steel input (+5%) for the loss during processing. A low-alloyed steel is used as main input material.
Automotive painting, electrocuting per m^2	**2.01**	m^2	This process was chosen for representing the door painting, assuming that this phase is carried out as in the automotive Industry. The alongside value is referred to the door painted surface
Transport, lorry 3.5-7.5 t, Euro 4	**2.061**	t*km	Raw material (steel) supply. A 50 km distance was considered on an average.
Steel waste to recycling	**1.96**	kg	

The thermal power plant was represented by an item, already existing in the Ecoinvent v.2.2 database, named “Heat pump 30 kW” where the FU is expressed as 1 p (amount). All the main input materials used for the pump production, as well as the energy and water requirements, were accounted for. Considering the lifetime of the heat pump in question, as well as of the shed, four replacements were foreseen, considering no differences between the technology of the pump production and working.

The entire air distribution system was not taken into account, because of the absence of project specific data and of low inventories that are expected in comparison to the other phases.

The energy demand for the indoor heating and cooling was represented by using the item “Electricity LV, use in I + import”, associating the sum of the two energy consumption contributes multiplied per the shed life-time (55 years). This was done assuming no changes in the annual energy consumption.

2.2.4 Shed end of life phase

This phase is concerned with the shed disassembly and the treatment chosen for the constituent materials. Table 6 reports the amounts of demolition waste to be treated.

Table 6 Amounts of demolition waste to be treated

Material	*Amount*	*Unit of measurement*	*End- life scenario*
Concrete (polystyrene and reinforcement included)	**991.785**	t	Sorting plant
Mineral wool	**778**	kg	Recycling
Cement-fibre slabs	**27.65**	t	Recycling
Fiberglass	**273**	kg	Incineration
Windows (plastic frame + double glazing)	**13.474**	t	Landfill (80%)+ Incineration (20%)
Metal doors	**704.145**	kg	Inert material landfill

Regarding concrete, considering the pre-cast concrete panels manufacturing techniques and the polystyrene amounts, while it is technically possible and even economically and environmentally convenient to separate it from the reinforcement steel, it is not justifiable to separate it from the polystyrene slabs used as thermal insulators. For this reason, a sorting treatment was considered so as to be able to separate each fraction from the other (concrete + polystyrene from steel) and then proceed with their recycle or reuse. In similar cases, concrete is generally reused in fact as roadbed, while reinforcement steel is recycled in appropriately equipped plants.

For representing this phase, the item "*Disposal, building, reinforced concrete, to recycling*" was used (Evoinvent v.2.2 database) considering the main input flows from dismantling to recycling.
Furthermore, the end-life treatment scenario for windows and doors were considered. For representing windows plastic frame and double glazing end-life, the Ecoinvent v.2.2 database was accessed so as to know about the scenarios considered: recycling is not one of them. In particular, double glazing is disposed of for 80% in landfill, while the remaining 20% goes to municipal waste incineration plants. Regarding plastic frame, Ecoinvent v.2.2 provides it to be entirely burned in municipal waste incinerators together with the metals parts, since too small to be efficiently collected and recycled. Same thing is for the metal doors. Checking in fact the Ecoinvent v.2.2 database, no steel-products recycling was found but only the disposal to inert material landfill: this is the process which was taken into consideration. These treatment solutions are believed to be not justifiable, since the entire component materials are produced and assembled so that they can be easily separated from each other and recycled. Furthermore, the life cycle of the shed in terms of overall environmental sustainability will be surely penalized and Life Cycle Impact Assessment results will be overestimated. The overestimation percentage will be able to be calculated, when developing the Life Cycle Impact Assessment phase, only if on-site-collectable data about recycling is available. With regard to the fiberglass skylights, only a municipal incineration is considered in the Ecoinvent v.2.2 database. In this case, the solution appears to be sensible, because they are damaged by the weather conditions, as well as by the thermal excursion, so as to be considered unrecyclable. Regarding mineral wool for roof insulation and cement-fibre slabs for roof covering, a recycling treatment was found within the database used and then applied.

3. Results and Discussion

The aim of this paper was to develop an LCI analysis of a pre-cast concrete shed used as a warehouse for non-perishing goods. This allowed the identification and quantification of the main input flows linked to the life cycle of the examined buildings facilitating the development of the next phase of impacts assessment, interpretation and improvement. The study results show that for the four phases taken into account in the system boundaries (production of the raw materials, construction of the shed, use of the shed and end of life of the shed) the most inventories are in the shed construction phase because of the huge amount of materials, fuels and resources such as concrete, steel, electrical energy and water. In particular, water is required for washing the precast concrete elements after being unmoulded, electrical energy and concrete for the construction of the shed; steel for the concrete reinforcement. Other inventories are mostly related:

- to the use phase, for the huge consumption of electrical energy linked to the thermal power plant use, in particular for the cooling operations in summer. to the maintenance phase, for the replacement of units such as fixtures and power plant;
- to the end of life phase, for the reinforced concrete waste transportation and recycling.

It is important to highlight that efforts were done to realize an LCI model as close to reality as possible using all the available data. In particular, the main difficulty found while developing the present study is attributable to collecting data from different sources, because of the number of stakeholders involved in the system analysed; for this reason, efforts were made to ensure the same data quality level. Nevertheless, some uncertainties could have resulted from:

- having excluded some processes, raw materials and products from the chosen system boundaries;
- some hypothesis and assumptions made in order to be able to use data reported in the Ecoinvent v.2.2 database;
- the assumption made about the end of life of the shed, taking into account its lifetime (50-60 years) and the impossibility of monitoring this phase.

Regarding the formworks and the PVC shutters as well, it would be useful to search for specific data from the field before conducting the whole LCA study. Same thing should be done for representing correctly the recycling of windows and steel service doors. This would allow for best-modelling, from an environmental perspective, the life cycle of the examined warehouse, obtaining results even more reliable.

As shown in Fig.1 and according to the ISO 14040:2006 and 14044:2006, “Interpretation” must be done for all the phases which LCA is divided in. At this step, Interpretation was done just for the LCI phase allowing for highlighting the most inventory processes within the shed life cycle. When the next phase of LCIA is developed, the Interpretation will be extended also to the environmental impacts caused by the system under study and to the improvement potentials.

4. Conclusions

The study attained the proposed goal, thereby clearly developing a detailed inventory analysis for a precast reinforced concrete shed life cycle and creating an accurate model to be further assessed from an environmental perspective.

Representative life cycle inventories are essential for any good quality life cycle assessment and can represent fundamental building blocks for compiling full life cycle assessment studies. As a matter of fact, on the basis of the LCI outcomes, the LCIA will be developed as the object of a future research so as to be able to assess the main impacts linked to the life cycle of the precast concrete shed in question. This second part of the study will allow identifying the most damaging processes, focussing the attention on the impacts of the raw materials and finished-products transportation compared to their production. The identification and environmental weighing of the impact indicators best representing the life cycle of the shed in question, such as kgeqCO_2, kgeqP.M.$_{2.5}$, MJ primary and so on, will also be done. Based on the LCIA results improvements hypothesis will be assessed towards a cleaner life cycle of the shed

Furthermore, the LCIA results will be able to be used for carrying out a comparative assessment with alternative materials, such as steel or wood, and so verifying any difference in terms of impacts on the environment.

An interesting aspect of the study, which to pay attention on, is about the usability of both the results from the inventory data and the environmental impacts analysis when environmentally assessing the life cycle of a good. In such cases, in fact, if the storage phase is included within the system boundaries, the warehouse building must be accounted for the share associated to the examined good.

Additionally, warehouses structural characteristics and environmental sustainability should be taken in consideration when intending to design goods storage and handling services adopting energy and environmental efficiency criteria. In this sense, using the results from the phases of inventory analysis and environmental impact assessment, the study will be useful to verify the contribution of the warehouse thus designed.

Lastly, it is important to highlight that this life cycle inventory, as well as the next phase of impact assessment, will be able to be applied to any other shed-type and so usable as a starting point for defining a standard procedure.

Contribution of authors

This article has been thought, discussed and written by the four authors and it is the result of their common commitment. In particular, C. Ingrao e A. Lo Giudice have contributed to bibliographical research, data collection-classification-evaluation, LCA development, while C. Mbohwa and M.T. Clasadonte to planning and final review of the research study.

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