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Environmental and economic sustainability in cultural heritage preventive conservation: LCA and LCC of innovative nanotechnology-based products

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ABSTRACT

The management of cultural heritage requires continuous preventive conservation measures, which are often expensive and can be impactful to the environment. Cultural heritage preventive conservation is currently experiencing the development of highly innovative techniques to improve the sustainability performance of materials (including nanomaterials) used in such activities. However, the impacts on human health and the environment that may result from the production and use of such (nano)materials are still largely unknown. The aim of this study is to assess the potential environmental and economic life cycle impacts of an innovative product called "Novel Archive Box" in which nanotechnology is applied for the preventive conservation of cultural objects stored in museum. Results based on the life cycle of one Novel Archive Box performed through the ReCiPe 2016 midpoint and endpoint method demonstrate a greater impact related to raw materials sourcing, including transport. The present work highlights the importance of applying screening Life Cycle Assessment and Life Cycle Costing to innovative products, since their early stage of development (e.g., prototype level), to support their further improvement and steer the arts and culture sector toward increasingly sustainable solutions.

1. Introduction

Preventive conservation is defined by the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) as "all measures and actions aimed at avoiding and minimizing future deterioration or loss. They are carried out within the context or on the surroundings of an item, but more often a group of items, whatever their age and condition. These measures and actions are indirect: not interfering with the materials and structures of the items or modifying their appearance." (ICCROM, 2022).

The standards set by museums for preventive conservation in many situations require highly airtight display cases for exhibiting works, storage boxes made of wood and archival boxes for storage in warehouses (Lucchi 2018). These containers can all be considered as semi-closed systems, which on the one hand protect objects, while on the other create a "microclimate" that can result in the release of volatile organic compounds (VOCs) or other gaseous pollutants that can cause or even promote the degradation of art materials (e.g. paint pigments) especially when composed of complex materials typical of contemporary artworks (D'Agostino et al., 2015).

In addition to the release of gaseous pollutants, degradation can also be promoted by fluctuations in the relative humidity and temperature; therefore stabilization of climatic conditions is indispensable for the preservation of artifacts (Boersma 2016).

In this context, nanotechnology can provide innovative and promising solutions to prevent and counteract the degradation processes of cultural objects and achieve long-term preservation of the cultural heritage (Baglioni et al., 2021). However, while preventive conservation is central to this process, it must be balanced against efforts to reduce the negative impacts of unsustainable resource use, waste generation, and climate change (Subramanian et al., 2015). Therefore, there is a clear need of a proper assessment and management of innovative nano-enabled products' environmental implications throughout their life cycle (Brunelli et al., 2021), to guarantee the adoption of safe and

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sustainable preventive conservation measures. A sustainable approach towards new materials and new technologies is now an unavoidable condition in all areas of innovation and production as set by the European Green Deal and the EU Action Plan Towards zero pollution for air, water and soil (European Commission 2021). Cultural heritage actively contributes to the sustainable development of our society and is recognized as a key of modern sustainability on the same level as other sectors (Di Turo and Medeghini 2021). To promote a sustainable approach to cultural heritage preventive conservation, attention should be paid to the impact assessment of all phases: from the environmental impacts generated by the production of the chemicals and devices used for restoration to the management of the waste resulting from such activities (Balliana et al., 2016).

Currently, sustainability is assessed by applying widely established tools for quantitatively determining the environmental (e.g., Life Cycle Assessment, LCA), economic (e.g., Life Cycle Costing, LCC), and social (e.g., Social Life Cycle Assessment, s-LCA) impacts of products, processes, and services across the entire life cycle (Caldeira et al., 2022a). The main current reference in the European landscape is the "Safe and Sustainable by Design chemicals and materials" framework by the Joint Research Center (JRC). This JRC report proposes a hierarchical stepwise approach in which safety aspects are considered, followed by environmental, social and economic sustainability aspects. This tiered approach also refers to information requirements since data availability is limited at the first stage of the research process. The framework foresees the assessment of the entire life cycle of a chemical or material, including the design phase and considering among others its functionality and end use (Caldeira et al., 2022b).

However, while the use of sustainability tools is spread in many industrial sectors, in the field of cultural heritage conservation it is still in its infancy (Blundo et al., 2018). In 2019, Semenzin et al. proposed a new framework for assessing the sustainability of nano-enabled products for the conservation of works of art that implement the Safe by Design concept. It adopts a tiered approach, which includes both screening and advanced assessment tools, to guide product developers in the development of innovative and sustainable nano-based products starting from the first stages of the innovation process (Semenzin et al., 2019). In such framework, LCA, LCC and s-LCA, are indicated as advanced tools for sustainability assessment, which are applicable when quantitative information become available about the products' life cycles.

While the application of LCA in the cultural heritage sector showed a recent growth (Blundo et al., 2014; Turk et al., 2017; Settembre Blundo et al., 2018; Franzoni et al., 2018; Mohaddes Khorassani et al., 2019; Sanchez et al., 2023), to the best of authors' knowledge only one LCC application on the production of materials or technologies for art conservation exists (Settembre Blundo et al., 2018).

This late response triggered the inclusion of sustainability assessment in the recently closed EU H2020 APACHE project (GA 814,496) aimed at supporting small and medium-sized museums in the use of appropriate technologies for preventive conservation, moving toward reducing the environmental impacts and costs of implementing and maintaining the control of climatic conditions and the presence of gaseous pollutants in the long-term storage of a wide range of cultural heritage artifacts, all from a sustainability perspective. The main output of the APACHE project was the design and production of several prototypes that use cost-effective nanotechnology for the active storage of artworks and cultural objects in different museum environments; their sustainability was evaluated through screening Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).

The aim of this paper is to assess, through LCA and LCC methods, the potential environmental and economic life cycle impacts of the APACHE innovative "Novel Archive Box", a corrugated cardboard box which enables an "active" preventive conservation of works of art. The box includes Sensor transponder, Relative humidity (RH) and Temperature (T) regulators and VOCs adsorbent, in which nanotechnology is applied, all developed in the frame of the research project. Therefore, this study represents the first example of both life cycle environmental and economic sustainability assessment of an innovative product for the preventive conservation of cultural objects. This work outlines the importance of applying screening Life Cycle Assessment to innovative products, since their early stage of development, to support their further improvement and steer the arts and culture sector toward increasingly sustainable solutions.

2. Materials and methods

The objective of the LCA and LCC study was to evaluate the environmental performance and cost, from the manufacturer's perspective, from cradle to grave, of the "Novel Archive Box" complete of sensor transponder, RH and T regulators and VOCs absorbent, as described in paragraph 2.1.1. Screening Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) were used to estimate the environmental and economic impacts along the life cycle, as the study was carried out at an early stage of product development.

LCA (ISO 14040:2021 and ISO 14044:2021) allows the assessment of the potential environmental impacts associated with a product, process, or service throughout its entire life cycle, from raw material extraction and processing, through manufacturing, transport, use and disposal. Attributional or consequential approaches can be used. Attributional LCA estimates what share of the global environmental burdens belongs to a product and allocation is performed by partitioning environmental burdens of a process along the life cycle. Consequential LCA estimates how the global environmental burdens are affected by the production and use of the product and allocation is avoided through the application of system expansion (Ekvall et al., 2016). In this study, LCA was performed following an attributional approach since the main objective was to quantify the current environmental impacts of the product.

LCC does not have a general standard that provides guidelines for its application; it is a management technique that aims at classifying and assessing costs according to the stages shaping the life cycle of a product or system (Knauer and Moslang 2018). Indeed, LCC aims not only to calculate the costs of acquiring raw materials, but also the costs of operation, maintenance, and final disposal (Hunkeler et al., 2008); thus, decision makers can act to improve the economic indicators of the system's life cycle (Toniolo et al., 2020). In the scientific literature, three possible types of LCC emerge, namely conventional LCC, environmental LCC, and societal LCC (Hunkeler et al., 2008). The conventional LCC is the assessment of all the costs associated with the life cycle of a product. The focus of the evaluation is on real, internal costs and sometimes the costs of the end of life are not included. Environmental LCC also includes environmental externalities and multi-stakeholders perspective. Societal LCC adds all costs covered by anyone in the society, whether today or in the long-term, through the inclusion of preferably all external costs in a monetarized form (Neugebauer et al., 2016). In this study a conventional LCC analysis, from the producers' point of view, was performed.

The LCA and LCC primary data were collected through specific questionnaires completed by the producers of the Novel Archive Box and of its components.

2.1. Goal and scope definition

The goal of the LCA and LCC study was to evaluate both the environmental performance from cradle to grave of the Novel Archive Box, and its overall costs from the point of view of the producers. The Novel Archive Box, namely a corrugated cardboard box which enables an "active" preventive conservation of works of art thanks to the inclusion of a Sensor transponder, RH and T regulators and VOCs adsorbent, was specifically developed for detection, monitoring and maintenance of microclimate parameters and air composition (T, RH and gaseous pollutants) ideal for the conserved object (Gawade et al., 2021). For this LCA and LCC study "1 Novel Archive Box" was defined as the functional unit.

2.1.1. Novel Archive Box

The box, i.e. the basic structure of the final product, is a corrugated cardboard box with the dimensions of 25 x 18 x 14 cm (L x W x H), including four "pockets" for the placement of the RH and T regulators, VOCs adsorbent and sensor transponder mentioned above and described in the following paragraphs.

2.1.1.1. Temperature regulator. Temperature regulator is characterized by polymer-based compounds consisting of Phase Change Materials (PCMs), functional materials capable of absorbing and releasing a large amount of heat during phase transitions (cycles of heating/cooling). In the Novel Archive Box, the application of a nano-PCM film to a piece of corrugated cardboard enables the T regulation within the relatively small box environment.

2.1.1.2. Humidity regulator. The humidity regulator is based on polyvinyl alcohol (PVA) and has been formulated with nano-agent cross-linkers and catalysts arranged on a membrane, which is able to absorb a larger amount of moisture than its surface area.

2.1.1.3. VOCs adsorbent. The VOCs absorbent consists of three raw materials: Fibrillated Cellulose, Colloidal Silica, and Polyethylenimine (Nanocellulose/Silica/PEI). The chemical and physical properties of nanocellulose and silica, such as high specific surface area, and the uniformly distributed PEI with a large number of functional groups, enhance the adsorption capacity of the material to capture NO_2 as well as other gases.

2.1.1.4. Sensor transponder. The electrochemical sensor included in the Novel Archive Box is capable of detecting changes in the conditions of the different parameters measured in the air and, unlike those already on the market, reduce heat loss allowing for greater product efficiency. The sensor then sends the collected information to a receiving system by Near Field Communication (NFC). NFC technology is a short-range wireless communication technology and is essential for monitoring the internal microclimatic conditions of a closed archive box with no need to open it and to use batteries (Gawade et al., 2021).

2.2. System boundaries

The diagram of the system under consideration is illustrated in Fig. 1.

In the LCA study the environmental impacts related to the Upstream, Core and Downstream stages of 1 Novel Archive Box are considered. All the main materials/components were purchased from different European countries: Italy, Sweden, Greece and Ireland. From these countries the main materials/components were transported by truck and aircraft to Germany where the manufacturing core process of the Novel Archive Box take place. The Novel Archive Box is assembled with the 4 components previously described: Temperature regulator, Humidity regulator, VOCs adsorbent and Sensor transponder. The production facility, in the Core stage, involves three main processes: cutting, assembly and folding. As depicted in Fig. 1, at Core stage used electricity and produced waste (the latter mainly due to packaging materials) are considered. At the end of the production, the Novel Archive Box is shipped from Germany to any country that needs it.

Since the Novel Archive Box is a prototype, for its end-of-life an incineration process is assumed.

For the LCC, the costs relative to Upstream (i.e., main materials/components and their transport) and Core (i.e., cutting, assembly, and folding) stages were considered. The shipment costs to other countries were not available and therefore were not included in the assessment. The costs related to the use and the end-of-life of the Novel Archive Box are not borne by the producer and consequently were not considered.

2.3. Life cycle inventory

For both LCA and LCC, primary data were collected in 2021 through specific questionnaires completed by the producers of the Novel Archive Box and of its components.

However, since both the final product and its components are prototypes, i.e. working models of an object not developed at large scale, several assumptions were made.

More specifically, information on product formulation, i.e. proportion of raw material composition, and personnel-related costs were provided with the highest level of accuracy. Assumptions were made for: transport of the main materials/components and of the final product, produced quantities, duration of the components and final product's

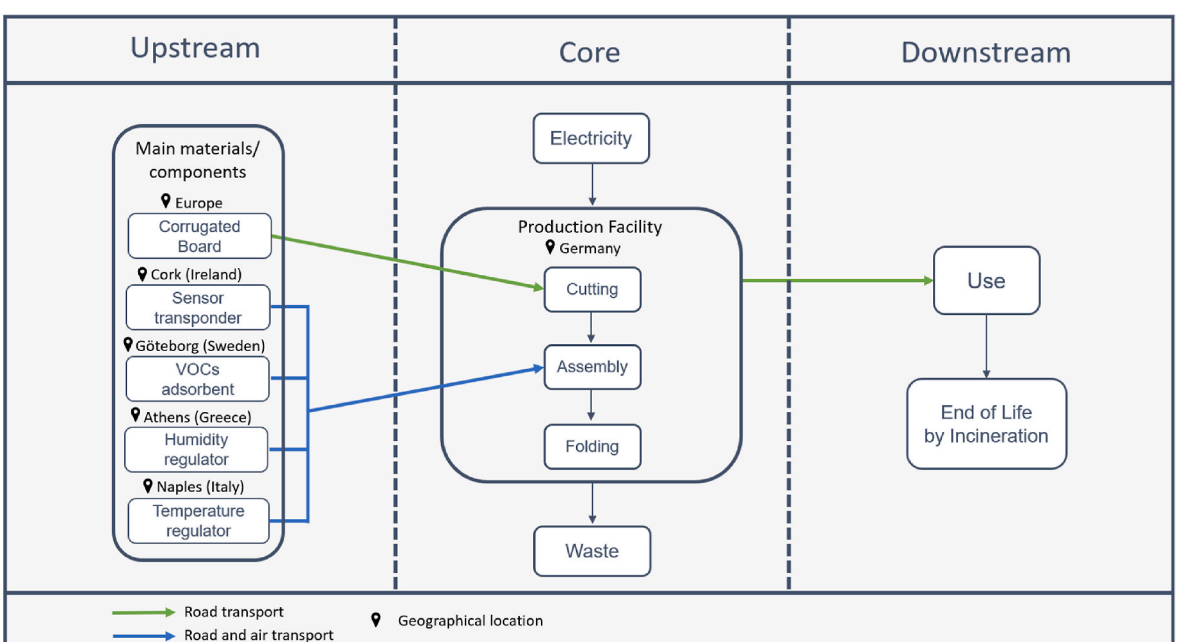

Fig. 1. Upstream, Core and Downstream-Use stages of the life cycle of Novel Archive Box.

lifecycle, type and frequency of their maintenance, methods of disposal, and costs related to raw materials' production, use, maintenance and disposal. Such data will be available when the Novel Archive Box will be at higher TRL (Technology Readiness Level).

2.3.1. Life Cycle Assessment (LCA) inventory

The assumptions made in the LCA study are the following.

- The means of transport by truck used for the transport of raw materials, main materials/components and the final product is: "Transport freight, lorry 16–32 metric ton, EURO5 {RER}| transport, freight, lorry 16–32 metric ton" from Ecoinvent 3.6.
- Carriage by air for the transport of the four components from Ireland, Sweden, Greece and Italy (Fig. 1) was modelled as: "Transport, freight, aircraft, very short haul {GLO}| transport, freight, aircraft, belly-freight, very short haul" from Ecoinvent 3.6.
- Where the waste treatment process was not indicated, treatment as municipal solid waste from Ecoinvent 3.6 was assumed for the specific countries producing T and RH regulators and VOCs adsorbent: "Municipal solid waste {specific country} | market for municipal solid waste", while the process "Municipal solid waste (waste scenario) {RoW}| treatment of municipal solid waste, incineration" was used for the sensor transponder and the Novel Archive Box.

Both the Novel Archive Box and its components were considered in its entirety and used with their background in the evaluation of impacts (Table 1). Table 1 reports all the LCA processes selected from the EcoInvent database v3.6 to model raw materials, water and energy sources and waste for both the Novel Archive Box and its four components.

2.3.2. Life Cycle Costing (LCC) inventory

The following costs of producing "1 Novel Archive Box" (i.e. Core stage only) were considered: i) personnel cost, ii) cost of main materials and components including the cost of their transportation (as split figures were not available for all the components), iii) cost of energy, iv) cost of waste collection and treatment, v) cost of water used, v) cost for the equipment maintenance borne by the producer. The costs of the transportation of the final product to customers were not included as they were not available. In Fig. 1, such transport activities are part of the Downstream stage.

2.4. Life cycle impact assessment

Both LCA and LCC were carried out with the use of the SimaPro LCA software developed by PRé Sustainability and the database EcoInvent Version 3.6 (Wernet et al., 2016). ReCiPe 2016 Endpoint and Midpoint methods were jointly used to calculate environmental impacts (Huijbregts et al., 2017). As the methods do not include characterization factors specific for nanoparticles release (Salieri et al., 2019), for this screening LCA nanomaterials were modelled as bulk materials.

For LCC, plausible costs as well as specific calculation methods were defined in the software.

Table 1
LCA processes from EcoInvent database v3.6 used to model the Novel Archive Box and its components.

Type	Raw materials	Process name in EcoInvent 3.6 (Cut-off) database
Temperature regulator		
Material	Cardboard	Corrugated board box {RER}| production
	Polybutylacylate(PBA)	Butyl acrylate {RER}| production
	Cellulosa (CELL)	Cellulose fibre, inclusive blowing in {GLO}| market for
	Phase Change Materials (PCM)	Soil pH raising agent, as CaCO3 {GLO}| lime to generic market for soil pH raising agent
	Packaging for further shipment	Corrugated board box {RER}| production
Energy	Electricity	Electricity, medium voltage {IT}| market for
Waste	Waste of the production	Waste packaging paper {SE}| market for waste packaging paper
Humidity regulator		
Material	Polyvinylalcohol (PVA)	Vinyl acetate {RER}| production
	Pyromelitic dianhydride (PMDA)	Sulfuric acid {RER}| production
	Maleic Acid (MA)	Maleic anhydride {RER}| production by catalytic oxidation of benzene
	Sulfuric Acid	Sulfuric acid {RER}| production
	p-toluenesulfonic acid (p-TSA)	Benzaldehyde-2-sulfonic acid {GLO}| benzaldehyde-2-sulfonic acid production
	Clynoptilolite	Zeolite, powder {RER}| production
Water	Distilled water	Water, deionised {Europe without Switzerland} | market for water, deionised
Energy	Electricity	Electricity, medium voltage {GR}| market for
Waste	Waste of the production	Municipal solid waste {GR}| market for municipal solid waste
VOCs adsorbent		
Material	Fibrillated Cellulose	Cellulose fibre, inclusive blowing in {GLO}| market for
	Colloidal Silica	Activated silica {GLO}| production
	Polyethylenimine (PEI)	Ethylamine {RER}| production
	Packaging for further shipment	Corrugated board box {RER}| production
Energy	Electricity	Electricity, medium voltage {SE}| market for
Waste	Waste of the production	Waste packaging paper {SE}| market for waste packaging paper
	Waste water	Municipal solid waste {SE}| market for municipal solid waste
Sensor transponder		
Material	Electronic components	Electronic component, active, unspecified {GLO}| production
	Carboard packaging material	Corrugated board box {RER}| production
Energy	Electricity	Electricity, medium voltage {EI}| market for
Waste	Waste of the production	Municipal solid waste {RoW}| treatment of municipal solid waste, incineration
Novel Archive Box		
Material	Temperature regulator	PCM treated corrugated cardboard
	Humidity regulator	PVA membranes
	VOCs adsorbent	VOCs adsorbent
	Sensor transponder	Sensor transponder
	Corrugated cardboard	Corrugated board box {RER}| market for corrugated board box
Energy	Electricity	Electricity, medium voltage {DE}| market for
Waste	Waste of the production	Municipal solid waste {DE}| market for municipal solid waste
	End of life	Municipal solid waste {RoW}| treatment of municipal solid waste, incineration

Table 2
Novel Archive Box LCA Midpoint results.

Impact category	Total	Corrugated cardboard	Temperature regulator	Humidity regulator	VOCs adsorbent	Sensor transponder	Core energy	Core Waste	EoL
Global warming - kg CO2 eq	1.50E+01	1.64E-01	5.72E-02	5.05E+00	3.79E-01	8.95E+00	8.13E-02	1.66E-01	1.22E-01
Stratospheric ozone depletion - kg CFC11 eq	8.32E-06	1.78E-07	4.62E-08	2.09E-06	3.28E-07	5.32E-06	5.74E-08	1.69E-07	1.27E-07
Ionizing radiation - kBq Co-60 eq	1.13E+00	1.51E-02	4.41E-03	1.46E-01	1.20E-02	9.33E-01	1.48E-02	3.07E-04	1.23E-04
Ozone formation, Human health - kg NOx eq	3.53E-02	4.99E-04	1.67E-04	6.21E-03	5.04E-04	2.77E-02	8.38E-05	1.15E-04	7.71E-05
Fine particulate matter formation - kg PM2.5 eq	3.19E-02	2.16E-04	6.84E-05	1.07E-02	2.57E-04	2.05E-02	4.31E-05	2.39E-05	1.57E-05
Ozone formation, Terrestrial ecosystems - kg NOx eq	3.58E-02	5.09E-04	1.70E-04	6.31E-03	5.16E-04	2.81E-02	8.47E-05	1.16E-04	7.75E-05
Terrestrial acidification - kg SO2 eq	6.24E-02	5.50E-04	1.88E-04	2.27E-02	6.57E-04	3.81E-02	1.40E-04	6.22E-05	4.11E-05
Freshwater eutrophication - kg P eq	2.39E-02	7.81E-05	1.73E-05	1.09E-02	5.62E-05	1.27E-02	1.15E-04	1.23E-05	9.22E-06
Marine eutrophication - kg N eq	1.27E-03	3.83E-05	6.38E-06	7.06E-04	3.42E-05	4.70E-04	7.34E-06	5.07E-06	2.62E-06
Terrestrial ecotoxicity - kg 1,4-DCB	3.59E+01	6.52E-01	1.76E-01	7.65E+00	9.93E-01	2.62E+01	5.06E-02	1.35E-01	6.07E-02
Freshwater ecotoxicity - kg 1,4-DCB	6.37E+00	7.46E-03	1.77E-03	3.47E-01	1.53E-01	5.71E+00	3.97E-03	8.56E-02	6.40E-02
Marine ecotoxicity - kg 1,4-DCB	8.38E+00	9.80E-03	2.34E-03	4.72E-01	1.99E-01	7.50E+00	5.31E-03	1.11E-01	8.32E-02
Human carcinogenic toxicity - kg 1,4-DCB	1.16E+00	5.00E-03	1.26E-03	5.60E-01	2.07E-02	5.46E-01	5.85E-03	9.94E-03	7.45E-03
Human non-carcinogenic toxicity - kg 1,4-DCB	1.06E+02	1.70E-01	4.10E-02	1.20E+01	2.68E+00	8.84E+01	1.25E-01	1.51E+00	1.12E+00
Land use - m2a crop eq	3.92E-01	6.74E-02	1.12E-02	1.63E-02	1.52E-02	2.79E-01	1.54E-03	4.59E-04	2.71E-04
Mineral resource scarcity - kg Cu eq	3.41E-01	4.70E-04	1.27E-04	2.68E-03	1.45E-03	3.36E-01	7.51E-05	8.12E-05	5.65E-05
Fossil resource scarcity - kg oil eq	4.01E+00	4.83E-02	1.78E-02	1.63E+00	3.99E-02	2.25E+00	1.95E-02	3.30E-03	1.60E-03
Water consumption - m3	1.20E-01	2.18E-03	7.03E-04	3.50E-02	2.71E-03	7.79E-02	4.55E-04	3.67E-04	2.71E-04

3. Results and discussion

3.1. Life Cycle Assessment (LCA) results

Midpoint results are presented in Table 2 as Characterized results for each impact category and main material (i.e. corrugated cardboard), components (i.e. T regulator, RH regulator, VOCs adsorbent, Sensor transponder) or specific process (i.e. Core energy, Core waste, End of Life). In the supplementary material, results are reported in more details, categorized by individual components of the Novel Archive Box (Table S1: Temperature regulator, Table S2: Humidity regulator, Table S3: VOCs adsorbent, Table S4: Sensor transponder).

In Fig. 2 the same results are reported as percentage, where each impact category result is set at 100% and relative contributions of different material/components/processes are presented in different colours. For each impact category, the most relevant contribution is provided by the Sensor transponder. This is due to three main reasons: i) the materials that compose the electronic parts (e.g., rare metals), as their extraction and processing phases heavily impact both quality and quantity of water resources; ii) the release of CO_2, zinc and particulate matter <2.5 μm into the environment due to the use of non-renewable energy along the Sensor transponder lifecycle; and iii) the long distances travelled by all the raw materials used in the production process. Only for *marine eutrophication* and *human carcinogenic toxicity* impact categories Humidity regulator provides the highest contribution, mainly explained by the relevant energy consumption during the PVA membranes production. Indeed, such energy is used to mix the blend, raise the temperatures of the mixture to 70 °C and 90 °C for many hours, and cure the membranes at 100 °C–140 °C. Finally, only for the *land use* impact category, the contribution of the main material Corrugated cardboard" is higher than the Humidity regulator contribution; this result can be explained by land occupation as natural forests are transformed into land for the cultivation of plants for commercial use.

The Core waste and the EoL processes contributions are far less relevant (<1.5% each, except for *stratospheric ozone depletion*), and can be noticed only in seven impact categories: *freshwater ecotoxicity*, *marine ecotoxicity* and *marine eutrophication*, due to the wastewaters produced during the production of PVA membranes; *human carcinogenic toxicity* and *human non carcinogenic toxicity*, due to the assumed waste treatment through incineration; and *global warming* and *stratospheric ozone depletion,* due to the large amount of air emissions produced by waste treatment.

Finally, the contribution of the energy used in the Core stage is even less relevant as it does not exceed 1.35% of the total impact in each midpoint category.

Endpoint results provide an overview of damages to *human health*, *ecosystems* and *resources,* generated by the environmental impacts caused by the life cycle of "1 Novel Archive Box".

The normalized results of the three endpoint indicators are reported in Fig. 3*: Novel Archive Box LCA endpoint results*. Similar to the midpoint results, the largest contributions to the calculated damages are related to the production of Sensor transponder and Humidity regulator. This is even more clear when considering the damage to *human health*, which is the most relevant endpoint caused by the Novel Archive Box lifecycle.

Both the energy consumed during the production of the Humidity regulator and the raw materials and transports involved in the Sensor transponder provide the highest contribution to the obtained endpoint results. *Human health* damage category is strongly affected by *global warming, fine particular matter formation,* and *human non-carcinogenic toxicity* midpoint impact categories. In the case of Humidity regulator, the relevant contribution to the first two midpoints (and therefore to the *human health* endpoint) is due to the large amount of electricity consumed to produce a very low amount of PVA membranes by weight. For Sensor transponder, the relevant contribution to all the three midpoints is due to rare metals that compose the electronic. This is mainly due to the fossil fuels and emissions of pollutants into the environment

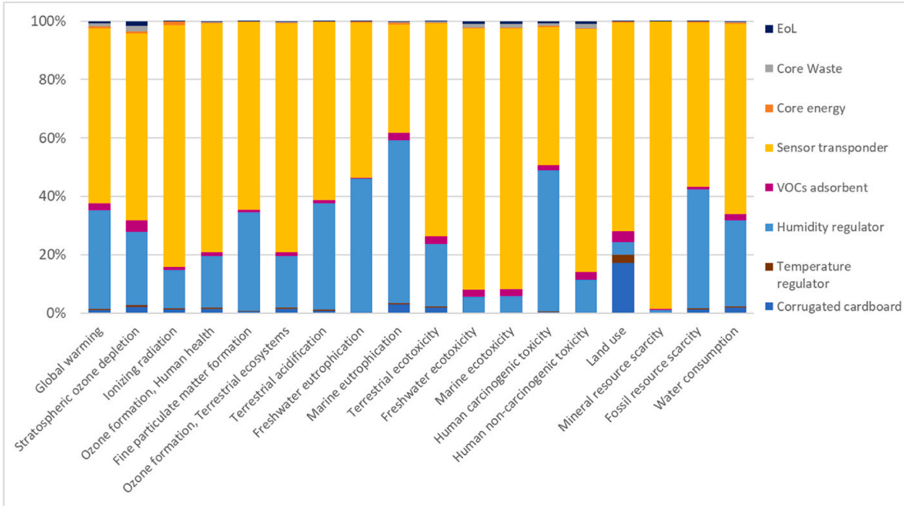

Fig. 2. Novel Archive Box LCA midpoint results.

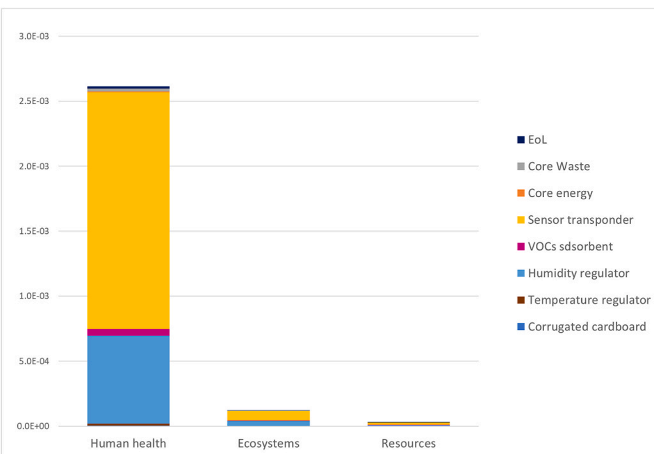

Fig. 3. Novel Archive Box LCA endpoint results.

for the extraction of metals, which mainly affects human health and ecosystems. This process also involves a large consumption of water that can no longer be used, and this aspect, along with the extraction of raw materials, negatively affects resource consumption.

The VOCs adsorbent results the second main components for environmental impacts caused. The damage to *human health* is mainly caused by both materials involved, cellulose and colloidal silica, and waste, which mainly impact on *human non-carcinogenic toxicity*. This is mainly due to both materials productions. The production of cellulose involves a large consumption of water, the use of fossil fuels and the release of CO_2 emissions. While for silica, the environmental impacts are mainly affected by the treatment of production waste.

The impact caused by PCM treated corrugated cardboard, which has the function of Temperature regulator, is due to the large amount of energy used to produce a very low amount of product by weight. For this Novel Archive Box component also the use of cardboard produced through water consumption and use of fossil fuels.

The contribution of Core and EoL waste treatment does not exceed 2% and is most impactful on the damage category of *human health*. The contribution of electricity consumption related to the energy core demand does not exceed 0.45% of the total impact and is most impactful on *resources*.

3.1.1. Sensitivity analysis

Since many of the main assumptions were made for transports, it was decided to further investigate the contribution of this process through a simple sensitivity analysis.

In particular, three main scenarios were identified and modelled selecting LCA processes available in Ecoinvent 3.6 (Cut-off) (Spielmann et al., 2007).

The first is a baseline scenario, which corresponds to the already presented study assumption involving a *16–32 metric ton* lorry for transport by truck (*Transport freight, lorry 16–32 metric ton, EURO5 {RER}| transport, freight, lorry 16–32 metric ton*) and a very-short haul (*Transport, freight, aircraft, very short haul {GLO}| transport, freight, aircraft, belly-freight, very short haul)* for the carriage by air.

The second, called Worst case, corresponds to scenario in which a EURO 4 unspecified size lorry is considered for the road transport by truck (*Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO4 to generic market for)*, while for the carriage by air a short haul aircraft is used (*Transport, aircraft, short haul {GLO}| transport, freight, aircraft, belly-freight, short haul*).

The third and last one is the Best case scenario in which a EURO 6 unspecified size lorry is considered for the road transport by truck (*Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for),* while for the carriage by air a medium haul aircraft is used (*Transport, freight, aircraft, medium haul {GLO}| transport, freight, aircraft, belly-freight, medium haul)*.

For each scenario, three possible transport distances were hypothesized: A) *standard routes*, which correspond to the distances assumed in the study (i.e., estimated average distances based on knowledge about the location of departure and arrival sites); B) *best routes,* where standard routes were decreased by 20%; *c) worst routes,* where standard routes were increased by 20%.

As shown in Table 3, the obtained results did not highlight significant differences among the three scenarios. While changing the type of road and air transport (with different emission standards for trucks and distance classes for aircrafts), there is no substantial change in the overall results. The same applies to the 20% difference in transportation distances, which did not result in significant changes in any of the calculated environmental impact categories.

3.2. Life Cycle Costing (LCC) results

This section reports the life cycle costs borne by the producer of "1 Novel Archive Box".

The economic impact is illustrated in Fig. 4 according to 8 cost categories: raw materials and transport, water, energy, wastes, packaging and transport, personnel, services, and equipment maintenance.

Table 3
Novel Archive Box LCA sensitivity analysis results.

Impact category	Baseline			Worst case			Best case		
	A	B	C	A	B	C	A	B	C
Global warming - kg CO2 eq	1.50E+01	−0.15%	+0.15%	−0.20%	−0.32%	−0.09%	−0.27%	−0.38%	−0.42%
Stratospheric ozone depletion - kg CFC11 eq	8.32E-06	−0.12%	+0.12%	−0.24%	−0.36%	−0.24%	−0.24%	−0.24%	−0.12%
Ionizing radiation - kBq Co-60 eq	1.13E+00	−0.09%	0.00%	−0.09%	−0.09%	0.00%	−0.09%	−0.09%	−0.09%
Ozone formation, Human health - kg NOx eq	3.53E-02	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fine particulate matter formation - kg PM2.5 eq	3.19E-02	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Ozone formation, Terrestrial ecosystems - kg NOx eq	3.58E-02	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	−2.86%
Terrestrial acidification - kg SO2 eq	6.24E-02	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Freshwater eutrophication - kg P eq	2.39E-02	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Marine eutrophication - kg N eq	1.27E-03	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Terrestrial ecotoxicity - kg 1,4-DCB	3.59E+01	−0.44%	+0.44%	−0.37%	−0.75%	0.00%	−0.42%	−0.78%	+0.39%
Freshwater ecotoxicity - kg 1,4-DCB	6.37E+00	0.00%	0.00%	−0.02%	−0.02%	0.00%	−0.02%	−0.02%	0.00%
Marine ecotoxicity - kg 1,4-DCB	8.38E+00	0.00%	0.00%	−0.01%	−0.01%	0.00%	−0.01%	−0.01%	0.00%
Human carcinogenic toxicity - kg 1,4-DCB	1.16E+00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Human non-carcinogenic toxicity - kg 1,4-DCB	1.06E+02	−0.01%	+0.01%	−0.01%	−0.02%	−0.01%	−0.01%	−0.02%	−0.01%
Land use - m2a crop eq	3.92E-01	−0.26%	0.00%	0.00%	−0.26%	0.00%	0.00%	−0.26%	0.00%
Mineral resource scarcity - kg Cu eq	3.41E-01	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fossil resource scarcity - kg oil eq	4.01E+00	−0.20%	+0.20%	−0.25%	−0.40%	−0.10%	−0.33%	−0.45%	−0.50%
Water consumption - m3	1.20E-01	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

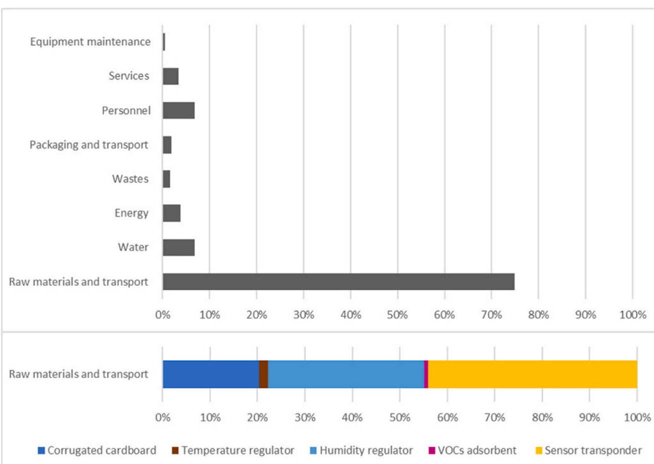

Fig. 4. Novel Archive Box LCC results with percentage of costs for each cost category.

Percentage results are reported for each cost category and their sum represents the 100% of costs to produce “1 Novel Archive Box”.

Since the major contribution is provided by *raw materials and transport* category, which accounts for 74.9% of the total cost, in Fig. 4 the contributions to this cost category of the main materials and components (i.e., Corrugated cardboard, Temperature regulator, VOCs Adsorbent, Sensor transponder, Humidity regulator) is also depicted.

As result, the most expensive “*Raw materials and transport*” are associated to the Sensor transponder (44%), followed by the Humidity regulator (33%) and the Corrugated cardboard (20%). In general, those costs are related to the purchase of the raw materials, involving high production costs.

Regarding the other cost categories, *Personnel* contributed for 6.9%, followed by *Water* (6.8%), *Energy* (3.79%), *Service* (3.38%), *Packaging and related transport* (1.98%) and *Equipment maintenance* (0.57%).

The cost of personnel derives from the cost of labour (per hour) in different countries and the time (hours) needed for the specific production. However, it should be noted that all the components and the final products are prototypes, therefore the produced quantities used in this study are estimates. The same applies also to the input data used for the other cost categories. This means that the performed LCC can be considered preliminary and could be improved once more detailed economic information will be available.

4. Discussion

The results obtained by the LCA study allowed to identify the potential environmental impacts of the Novel Archive Box, divided according to main material (i.e. corrugated cardboard), components (i.e. T regulator, RH regulator, VOCs adsorbent, Sensor transponder) and specific processes (i.e. Core energy, Core waste, End of Life).

Overall, the results showed that the upstream phase provides the highest contribution to the environmental impact of the Novel Archive Box. In particular, the Sensor transponder is the component contributing the most, due to the raw materials (e.g., rare metals) that compose its electronic parts. However, the results uncertainty is quite high as detailed information about used raw materials, production process and travelled distances were not made available. As an example, modelling of the Sensor transponder had to be simplified because, on one hand, not enough detailed information on the electronic parts (including e.g. NFC loop antenna and NFC radio) of the hardware prototype were provided. On the other hand, in the Ecoinvent database only one process was available to model an electronic component such as the Sensor transponder (*Electronic component, active, unspecified {GLO}| production*). Upstream phase modelling can surely be improved, and results uncertainty be reduced once more primary data will be available, i.e. moving from a prototype to a more advanced development stage.

The lack of relevant Ecoinvent processes was also the reason for not performing a sensitivity analysis on the raw materials used in the different components. Instead, it was performed on upstream and core transports, for which several assumptions were made. However, the obtained results did not highlight any significant difference when changing type of road and air transport as well as transportation distances.

Another limitation of this study refers to the inclusion of specific nanotechnology data. Currently, LCI data for nanomaterials and nano-enabled products are scarce. Indeed, despite the ongoing research efforts to assess both nanomaterials (eco)toxicity and release into the environment, there is a lack of specific characterization factors (CF) to be used in life cycle impact assessment (LCIA) (Salieri et al., 2018). Moreover, accurate information about the end-of-life management of waste nanoproducts are missing (Nizam Nurul Umairah et al., 2021).

The results of the LCC study are also preliminary and can be improved once more detailed information will be available. Moreover, since a conventional LCC approach was applied, which assessed only internal costs, a possible improvement could be the inclusion of externalities as some critical raw materials (i.e., materials of high economic importance and high supply risk)(Rödger et al. 2017) are used in the production of the Novel Archive Box components.

Finally, another aspect that could be evaluated in the future is the social dimension of sustainability. However, this is probably the most difficult aspect to address at a prototype stage and so far, the least evaluated (Stoycheva et al., 2022).

5. Conclusions

The screening LCA and LCC study evaluated the environmental and economic implications of "1 Novel Archive Box" along its life cycle. The Novel Archive Box, namely a corrugated cardboard box which enables an "active" preventive conservation of cultural objects thanks to the inclusion of Sensor transponder, RH and T regulators and VOCs adsorbent, has been specifically developed for detection, monitoring and maintenance of microclimate parameters and air composition (T, RH and gaseous pollutants) ideal for the conserved objects.

Regarding environmental impacts (both at midpoint and endpoint levels), obtained results highlighted that the upstream phase provides the major contribution, and in particular the materials used for both the Novel Archive Box and its components, and their transport. Indeed, in some cases (e.g., for the Sensor transponder) critical raw materials are used, which have significant impacts on several midpoints, including those related to the quality and quantity of water resources. On transport, for which several assumptions were made, a sensitivity analysis was performed resulting in negligible differences among three scenarios characterized by different types of road and air transport as well as transportation distances.

Regarding economic impacts, also the evaluation of the costs borne by the producers showed a major contribution by the *raw materials and transport* category.

However, it must be noted that for both LCA and LCC the obtained results are preliminary as the level of details provided at this early stage of the Novel Archive Box development is quite low. Nevertheless, they provided useful insights for improving such innovative product in the next development stages.

Future LCA and LCC applications will surely benefit from a larger set of primary data, and will probably reflect changes in the production process (e.g., to adapt it to large-scale production), and in the final selection of raw materials (e.g. characterized by less impactful extraction methods), and suppliers (e.g., geographically closer to the manufacturing site).

To conclude, LCA proved to be a useful tool in a screening phase for assessing potential environmental impacts of innovative materials, products and technologies in order to select cleaner production processes, avoid hazardous materials, maximise the efficiency of the energy used for production and for the product in use, and design waste management and recycling.

Although there are still some critical aspects that need to be addressed in future studies, LCA and LCC of innovative products, at the prototype development stage, can support research, development, and optimization by steering the arts and culture sector toward increasingly sustainable solutions.

This study is the first attempt to conduct both life cycle environmental and economic sustainability assessment of an innovative product for the preventive conservation of cultural objects, and as such it provides a basis for future research. In the ongoing HEU GREENART project (GA 101060941) a similar methodological approach is being adopted to further improve some of the innovative products developed in APACHE, by using green materials and low-energy consumption production routes to boost their sustainability. In GREENART, the methodology is even more comprehensive as it follows the recently published EU JRC *SSbD (Safe and Sustainable by Design) for chemicals and materials* framework (Caldeira et al., 2022b), which has immediately become the reference framework at EU level in the field of sustainable chemistry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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