Using a glass-fibre reinforced polymer composite in the production of sustainable water storage tanks

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Abstract: The present work focuses on the use of the life cycle assessment (LCA) and life cycle costing (LCC) methodologies to evaluate environmental and economic impacts of polymers and polymer composites materials and products. Initially a literature review is performed in order to assess the scope and limitations of existing LCA and LCC studies on these topics. Then, a case study, based on the production of a water storage glass-fibre reinforced polymer (GFRP) composite storage tank, is presented. The storage tank was evaluated via a LCA/LCC integrated model, a novel way of analysing the life cycle (LC) environmental and economic performances of structural products. The overarching conclusion of the review is that the environmental and economic performances of polymers composites in non-mobile applications are seldom assessed and never in a combined integrated way.

Keywords: life cycle thinking; life cycle assessment; LCA; life cycle costing; LCC; polymer composite; water storage tanks.

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1 Introduction

Materials selection plays a critical role in the quest for sustainability. However, this is not an easy task, as more than 160,000 materials are currently available for the design and manufacturing of products (Ashby, 2011). To attain that ultimate target, the designer can use several methods and tools, amongst them life cycle assessment (LCA) (ISO, 2006a, 2006b) and life cycle costing (LCC) (Ciroth et al., 2008; Swarr et al., 2011). Both LCA and LCC take into account the full life cycle of a product, from raw material extraction, production to use and final disposal, in a systemic approach. Only with such an encompassing approach it is possible to recognise and address conflicting trade-offs that arise when selecting alternative materials or products (Klöpffer, 2003, 2005, 2008; Norris, 2001; Zamagni, 2012). Although still evolving, the LCA methodology, as well as the complementary economic analysis, have already been integrated in product development processes, using different approaches (Nakano and Hirao, 2011; Simões et al., 2012a). But more studies still need to be done to consolidate this integrated methodology, in particular in what concerns plastic materials.

In the last decades, plastics consumption worldwide has increased at an average yearly rate of about 8%, attaining an all times maximum in 2013, at 299 million tonnes (Plastics Europe, 2015). Further, the production of plastics is energy intensive and their end of life (EoL) is difficult to manage. These and other considerations led to an increasing number of publications on the environmental and economic consequences of making, using and disposing of plastic products. Initially the more relevant publications were based on LCA and later on LCC studies. A number of general conclusions have emerged from these publications that warrant reviewing. Thus, it was considered of interest to assess the scope of published LCA and LCC studies on polymer and polymer matrix composites, focussed on specific environmental impact categories, such as *global warming potential* and *total energy use*. These categories were selected as almost all studies consider them, due to the importance given to the enhanced greenhouse gas effect. Table 1 summarises the results obtained. Some studies also report data on other impact categories, such as *ozone layer depletion potential*, *photochemical oxidation*, *acidification and eutrophication*, but, as this is not a general feature, they were not included in the table.

Table 1 LCA studies comparing polymers and polymer composites with traditional materials

Reference	*Material*	*Global warming potential*	*Total energy use*
Das (2011)[1]	S; CFRP	CFRP < S	S < CFRP[a]; CFRC ≈ S[b]
Ibbotson et al. (2013)[2]	SS(r); SS(su); FRP(su)	-	SS(r) < FRP(su) < SS(su)
Ibbotson and Kara (2013)[3]	SS; GFRP	SS ≈ GFRP	-
Khanna and Bakshi (2009)[1]	S; CFRP	-	S < CFRP[a]; CFRP < S[b]
Puri et al. (2009)[1]	S; A; GFRP	GFRP ≈ A < S	GFRP ≈ A < S
Roes et al. (2007)[1,4,5]	PP; LDPE; GFRP[c]; PPC[d]	PP ≈ PPC; PPC < LDPE; GFRP ≈ PPC	-
Saur et al. (1996)[1]	S; A; SMC; PPO/PA	SMC < S < PPO/PA < A[a] PPO/PA < SMC < A < S[b]	SMC < S < PPO/PA < A[a] SMC < A < PPO/PA < S[b]
Schwab-Castella et al. (2009)[1]	SS; A; HCFRP; FCFRP	FCFRP < HCFRP< <A < SS	-
Simões et al. (2012b)[3]	S; A; GFRP	A < S < GFRP	-
Song et al. (2009)[1]	S; A; GFRP	-	A < GFRC < S
Suzuki and Takahashi (2005)[1]	S; CFRP; rCFRP	-	rCFRP < S < CFRP[a]
Suzuki et al. (2005)[1]	S; CFRP; rCFRP	-	rCFRP < CFRP < S[b]
Witik et al. (2011)[1]	M; S; GMT; SMC; GFRP; CFRP	SMC < GFRP < GMT < < CFRP < S < M	-
Witik et al. (2012)[6]	Auto CFRP; OOA CFRP	OOA < Auto	OOA < Auto

Notes: Applications: [1]automotive; [2]medical; [3]construction; [4]packaging; [5]agricultural; [6]aerospace.

[a]System boundary up to the manufacture stage, 'cradle-to-gate' analysis; [b]System boundary up to the EoL stage, 'cradle-to-grave' analysis; [c]PP composite using virgin PP and 30 wt% glass fibre; [d]PP composite using virgin PP and nanoclay silicate.

Key – A: aluminium; Auto: autoclave; CFRP: carbon fibre reinforced polymer; FCFRP: full CFRP composite; FRP: fibre reinforced polymer; GFRP: glass fibre reinforced polymer; GMT: glass fibre mat thermoplastic; HCFRP: hybrid CFRP composite; LDPE: low density polyethylene; M: magnesium; OOA: out-of-autoclave; PP: polypropylene; PPC: polypropylene composite; PPO/PA: injection moulded polymer blend of polypropylenoxide (PPO) and nylon (PA); rCFRP: recycled carbon fibre reinforced polymer; S: steel; SMC: glass fibre and unsaturated polyester resin sheet moulding compound; SS: stainless steel.

Table 2 LCC studies comparing polymers and polymer composites with traditional materials.

Reference	*Material*	*Economic analysis method*	*Cost results*
Albrecht et al. (2013)[1]	W(su); CB(su); P(r)	LCC (excludes externalities)	P(r) < W(su) < CB(su)
Alves et al. (2009)[2]	GFRP[a]; NFRP[b]	Economic analysis (semi-quantitative, excludes externalities)	NFRP < GFRP
Alves et al. (2010)[2]	GFRP; NFRP[c]	Economic analysis (excludes externalities)	NFRP<GFRP
Ibbotson et al. (2013)[3]	SS(r); SS(su); FRP(su)	LCC (total cost of ownership – TCO, excludes externalities)	SS(r) < SS(su) < < FRP(su)
La Rosa et al. (2013)[4]	GFRP[d]; NFRP[e]	LCC (excludes externalities)	NFRP < GFRP
Lloyd and Lave (2003)[2]	S; A; PPC[f]	Economic analysis (technical cost modelling – TCM, excludes externalities)	PPC ≈ A < S
Roes et al. (2007)[1,2,5]	PP; LDPE; GFRP[g]; PPC[h]	LCC (excludes externalities)	PP ≈ PPC PPC < LDPE PPC < GFRP
Schwab-Castella et al. (2009)[2]	SS; A; HCFRP; FCFRP	Economic analysis (TCM, excludes externalities)	FCFRP < HCFRP ≈ ≈ A < SS
Witik et al. (2011)[2]	M; S; GMT; SMC; GFRP; CFRP	Economic analysis (TCM, excludes externalities)	SMC < GFRP < GMT < < M < CFRP < S
Witik et al. (2012)[2]	Auto CFRP; OOA; CFRP	Economic analysis (TCM, excludes externalities)	OOA ≈< Auto
Zah et al. (2007)[2]	GFRP[i]; NFRP[j]	Economic analysis (qualitative, excludes externalities)	NFRP < GFRP

Notes: Applications: [1]packaging; [2]automotive; [3]medical; [4]construction; [5]agricultural.

[a]Unsaturated polyester glass fibre composite; [b]jute fibre unsaturated polyester composite; [c]untreated and treated jute fibre unsaturated polyester composite; [d]epoxy vinyl ester glass fibre composite; [e]epoxy vinyl ester glass fibre and hemp fibre composite; [f]clay reinforced virgin PP; [g]30 wt% glass fibre reinforced virgin PP; [h]nanoclay silicate reinforced virgin PP; [i]glass fibre reinforced virgin PP; [j]curauá fibre reinforced virgin PP.

Key - A: aluminium; Auto: autoclave; CB: cardboard; CFRP: carbon fibre reinforced polymer; FCFRP: full CFRP composite; FRP: fibre reinforced polymer; GFRP: glass fibre reinforced polymer; GMT: glass fibre mat thermoplastic; HCFRP: hybrid CFRP composite; LDPE: low density polyethylene; M: magnesium; NFRP: natural fibre reinforced polymer; OOA: out-of-autoclave; P: plastic; PP: polypropylene; PPC: polypropylene composite; r: reusable; S: steel; SMC: glass fibre and unsaturated polyester resin sheet moulding compound; SS: stainless steel; su: single-use; W: wood.

The first and foremost conclusion of the Table 1 is that in most studies comparing the environmental impact of alternative materials, plastics often present quite positive LC profiles Further, the results also show that, in most cases, the use of fibre reinforced polymer (FRP) composites generates the lowest (or similar) environmental impact in the abovementioned categories. The few conflicting data present in Table 1 may be explained by factors such as the definition of the system boundaries and type of EoL treatment. In the case of FRP composites, the inclusion of all LC phases, namely the EoL treatment option, usually influences negatively their comparison with traditional materials (Das, 2011; Khanna and Bakshi, 2009; Saur et al., 1996). This reflects the fact that at EoL most FRP composites are still deposited in landfills with little recycling/recovery being done. Another interesting feature that emerges from the table is the high proportion of automotive application studies. In these studies, the use phase has been intensively assessed, since it is known to be very energy intensive and therefore resulting in high environmental impacts. This fostered the introduction of lighter materials, such as FRP composites, to decrease fuel consumption (Das, 2011; Khanna and Bakshi, 2009; Saur et al., 1996; Puri et al., 2009; Roes et al., 2007; Schwab-Castella et al., 2009; Song et al., 2009; Suzuki and Takahashi, 2005; Suzuki et al., 2005; Witik et al., 2011). On the other hand, much less LCA studies were devoted to non-mobile, structural applications of such composites (Ibbotson and Kara, 2013; Simões et al., 2012a, 2012b).

Literature reporting the LC economic assessment of polymers and polymer composites is scarcer than that reporting their LC environmental assessment. In fact, the prime focus of almost all studies reviewed is the evaluation of environmental impacts, the economic and social assessment being a secondary objective. Table 2 summarises published LCC studies comparing polymers and polymer composites with traditional materials.

The table shows that the LCC methodology is still controversial, since different economic analysis methods were used in the studies therein. All of them are limited to a financial cost analysis, excluding externalities. Automotive applications are again highly represented. The results reported in the Table 2 are once more consistent, showing that the use of polymers and polymer composites has the lowest (or similar) economic impact in all but one of the references reviewed. The one conflicting result (Ibbotson et al., 2013) may be explained by the specificity of the use phase (a medical application) and also due the possibility of reuse. Indeed, conventional material products may be preferable to composite ones when they can be reused a number of times large enough to mitigate their higher material cost. Although lateral to the focus of the present work, it can also be concluded from Table 2 that the use of natural fibres has the potential to decrease materials costs. Finally, a comparison of Tables 1 and 2 reveals that very few studies address the environmental and economic impacts concurrently (Ibbotson et al., 2013; Roes et al., 2007; Schwab-Castella et al., 2009).

Summing up, the main conclusion of the review performed is that few studies address non-mobile applications of FRP composites and even fewer include their concurrent LCA/LCC evaluation. Thus, in the present work, a concurrent analysis of the LC environmental and economic performances of a structural product was made. A glass-fibre reinforced polymer (GFRP) composite tank designed to store treated water before distribution (Bhardwaj, 2001), and two different EoL scenarios, deposition in landfill and incineration with energy recovery, were chosen. The results provide insights into the synergies existing between the environmental and economic performances of composite products and the influence of the EoL option in their global environmental impact.

2 Methodology

The LCA/LCC integrated framework adopted, which includes all stages of a product's life (Simões et al., 2012a), consists in a parallel assessment, using the LCA methodology according to the ISO 14040 series (ISO, 2006a, 2006b), and the LCC methodology based on the SETAC guidelines (Ciroth et al., 2008; Swarr et al., 2011). The LCA/LCC model involves implementing the LCA methodology to the product system and, in parallel, incorporating its results into the LCC study, namely those of the life cycle inventory (LCI) and life cycle impact assessment (LCIA). The goal and scope phase of the LCC should be consistent with that of the LCA. The main issue to consider is the use of the same functional unit and system boundaries in both methodologies.

3 Results and discussion

The product chosen is a commercial horizontal tank capable of holding 50 cubic metres of drinking water at atmospheric pressure. Accessories, such as supply and drain connections, suspension eyebolts, vent pipe, liquid level indicator and man hole were also included in the analysis. Adjacent processes and materials, such as water pumps, piping supply, valves, energy to pump water and the water used during the whole LC, were excluded. The composite tank, having a cylindrical shell and top/bottom accessories, processed by filament winding and hand-lay-up, respectively, was designed according to BS 4994-1987 using as base material a fibre-glass reinforced isophthalic polyester resin. A significant part of the data upon which the analysis was based was obtained in real industrial conditions in one firm in the North of Portugal. The tank lifespan depends on the construction material and local weather conditions (e.g., salty sea air). The actual lifespan of this product is not yet completely known. The manufacturer's estimates that lifespan to be longer than 30 years. In fact, it was never necessary to substitute a tank due to material damage in that period. Therefore, a tank with a lifespan of 30 years was defined as the functional unit in the present work.

3.1 Life cycle assessment

The LCA is based in a 'cradle-to-grave' assessment, which considers the raw materials production, tank production, onsite installation, use and maintenance, dismantlement and EoL treatment and all intermediate transport processes. It is supposed that no maintenance is needed during the use phase. The R&D, installation and dismantlement LC phases were excluded from the study. It is also supposed that at the end of its useful life the tank is sent to the nearest landfill to be properly treated. The stainless steel accessories are separated and sent for recycling. However, as mentioned before, another EoL scenario, incineration with energy recovery, was considered, since in some Portuguese regions it is possible to choose this treatment option. The data corresponding to all processes is presented in Table 3. The EoL scenarios were modelled under the following assumptions:

1 landfill, considering no environmental credits

2 incineration with energy recovery, considering that generation of fossil fuels (crude oil)-based electricity was averted

3 recycling, considering that production of stainless steel was avoided.

The systems were modelled using commercial databases (Ecoinvent database, 2007; Buwal 250 database, 1996; IDEMAT database, 2001) and field data, which were ultimately summarised in the LCI performed in SimaPro 7 (SimaPro 7.3, 2011). The LCIA was carried out using the Eco-Indicator 99 (EI99) method (Goedkoop and Spriensma, 2001). Figures 1 and 2 present, on a functional unit basis, the relative characterisation results of the tank, excluding (Figure 1) and including (Figure 2) the EoL stage.

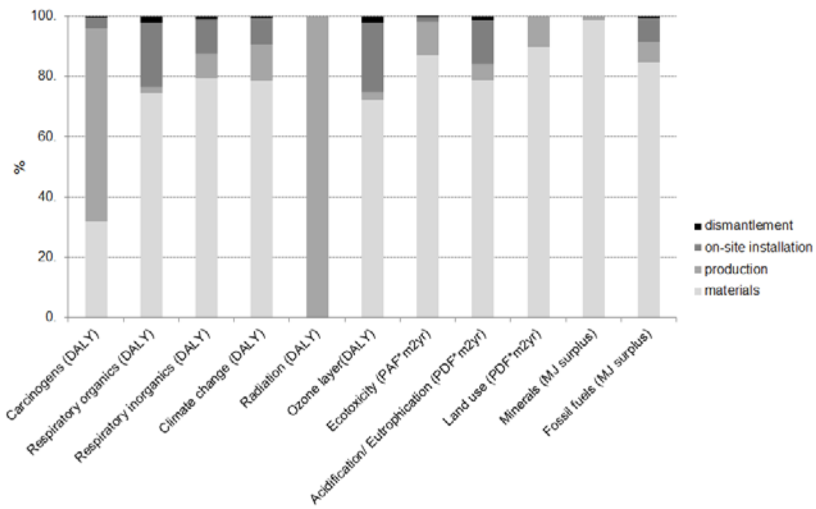
Table 3 Input data for the tank system on a functional unit basis

Process		*Input*	*Source*^(database)^
Raw materials	Polyester resin	705.55 kg	Polyester (unsat) I[1]
	Glass fibre	724.86 kg	Glass fibre I[1]
	Stainless steel	22.60 kg	X5CrNi18 (304) I[1]
Tank production	Electricity	480 kWh	Electricity, medium voltage, production PT, at grid/PT U[2]
	Polyester resin	6.82 kg	Polyester (unsat) I[1]
	Glass fibre	7.25 kg	Glass fibre I[1]
Transports	Polyester resin	345 km	Truck 28t B250[3]
	Glass fibre	1,885 km	Truck 28t B250[3]
	Production waste to EoL (Landfill)	17 km	Truck 28t B250[3]
	Delivery to client	550 km	Truck 28t B250[3]
	Transport to EoL	50 km	Truck 28t B250[3]
EoL	Landfill	1,430.40 kg	Disposal, glass, 0% water, to inert material landfill/CH U[2] Disposal, plastic plaster, 0% water, to inert material landfill/CH U[2]
	Recycling (stainless steel)	22.60 kg	Recycling ECCS steel B2503, dataset adapted to X5CrNi18 (304) I[1]
	Incineration*	1,430.40 kg	Incin. Glass 1995 B250 (98)[3] Incin. PE 1995 B250 (98) avoided[3]

Notes: *EoL alternative scenario.
[1]IDEMAT database,
[2]Ecoinvent database,
[3]Buwal 250 database.

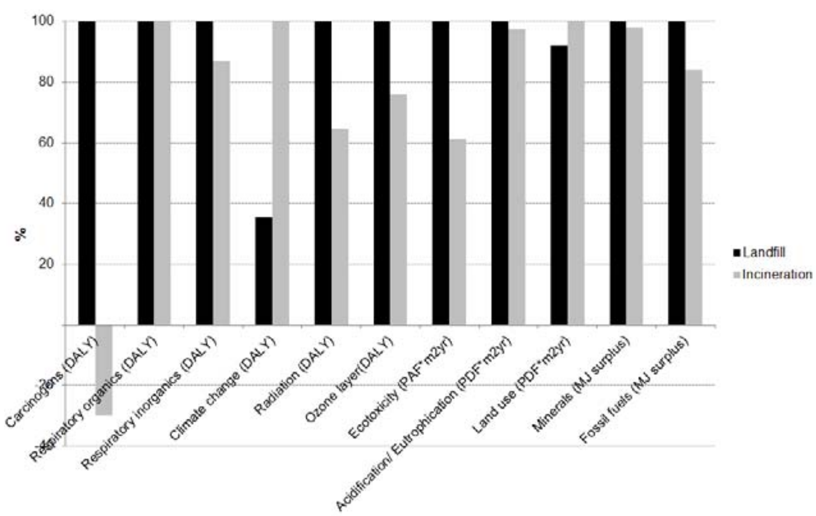
Figure 1 reveals that the production of raw materials (the GFRP composite) has the highest emission values in all but two (*carcinogens* and *radiation*) environmental categories. In these categories the major contributor is the tank production phase. The high impact of the raw materials production is mainly due to the energy intensive process used to manufacture the glass fibres.

Figure 1 Characterisation results of the tank system, excluding the EoL stage



Notes: *DALY:* disability adjusted life years (years of disabled living or years of life lost due to the impacts); *PAF:* potentially affected fraction (animals affected by the impacts); *PDF:* potentially disappeared fraction (plant species that disappear as result of the impacts); *MJ surplus:* surplus energy (MJ) (extra energy that future generations must use to extract scarce resources).

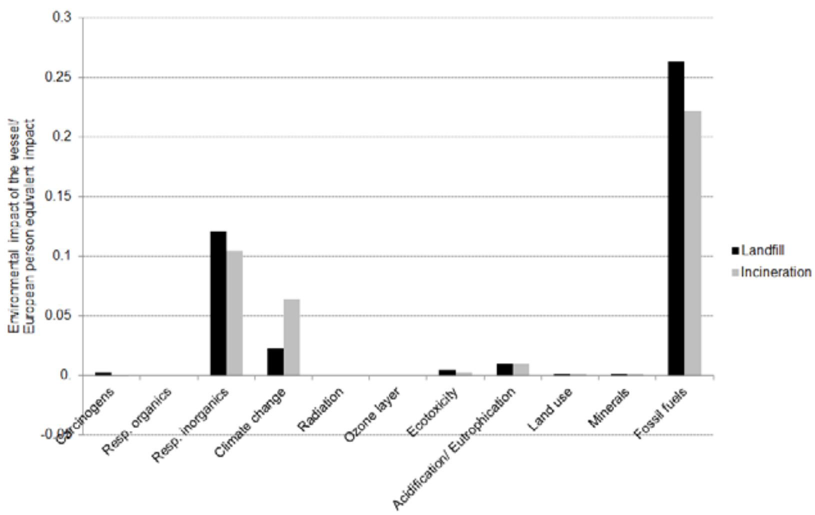
Figure 2 Characterisation results of the tank system, including the EoL stage



The tank with landfill as EoL option depicts the worse environmental profile (Figure 2), with higher values in all environmental impact categories, except in the *climate change* and *land use* ones. Moreover, in the incineration with energy recovery EoL scenario *fossil fuels* environmental impact category decreases 16%, due to the energy recovered from the burning of the polymer matrix. Conversely, the *climate change* environmental impact increases 64%.

The results depicted in the figures are consistent with those of previous studies (Arena et al., 2003; Björklund and Finnveden, 2005) that showed that environmental savings in non-renewable resources (crude oil, natural gas and coal), as well as increases in greenhouse emissions, occur when incinerating waste plastics. As usual, when the characterisation results do not directly led to univocal conclusions, a normalisation phase is enlightening. The tank normalisation results for the two alternative EoL options are depicted in Figure 3, on a functional unit basis. The figure shows that the *fossil fuels*, *respiratory inorganics* and *climate change* categories, by that order, represent the most significant burdens, in terms of scale of contribution.

Figure 3 Normalisation results of the tank system, including the EoL stage



3.2 *Life cycle costing*

In the integrated LCA/LCC model used in the present work the functional unit, system boundaries and other assumptions were the same in the two EoL scenarios. In this way, the LCC methodology can be used to identify and compare all associated cost drivers, based on a full LC perspective (producer perspective plus implications for market success due to use and disposal costs). The selected reference year was 2013, and the discount rate 3.5%. A societal LCC, which considering both internal and external economic aspects (Ciroth et al., 2008) was additionally chosen. Costs of CO_2 eq. emissions were accounted for based on the carbon tax established by the EU Emissions Trading System (Point Carbon, 2012). Damage costs corresponding to SO_2, NO_x and fine particles emissions were accounted for, based on the ExternE project as adapted by NETCEN

(Watkiss and Holland, 2000). The economic inventory includes LCI and LCIA results from the LCA study and additional financial information. Budget and market costs were used for conventional costs of all LC stages. Due to confidentiality requirements the results shown in Table 4 are reported simply as 'monetary units'. The tank system depicts very different potential internal and external LC costs, the former being about 99% of the total cost. Two stages, the tank manufacture, followed by the raw materials production, are the main contributors to that cost. The incineration with energy recovery scenario shows a marginally lower potential internal cost, due to the revenues that accrue from the sale of electricity.

Table 4 Total, internal and external costs of the tank system for the two EoL treatment scenarios

Life cycle stage	*Costs (monetary units/tank system)*		
	Total	*Internal*	*External*
Raw materials production	0.289	0.287	0.002
Tank manufacture	0.669	0.669	0.000
Onsite installation	0.035	0.034	0.001
Use and maintenance	0.000	0.000	0.000
Dismantlement	0.010	0.010	0.000
EoL – landfill	–0.003	–0.003	0.000
EoL – incineration	–0.004	–0.005	0.001

4 Conclusions

The present work presents a literature review of LCA and LCC studies of polymer and polymer matrix composites, focussed on specific impact environmental categories. It was concluded that, contrarily to the general perception, plastics and polymer matrix composites present in most cases a better life cycle environmental profile and also lower cost than alternative materials. The review also showed that very few studies were done on structural, non-mobile applications, of such composites and even fewer presented an integrated, concurrent environmental/economic assessment. A combined environmental and economic LCA of a GFRP composite tank was thus performed, comparing two alternative EoL scenarios: landfill and incineration with energy recovery. The analysis allowed identifying the environmental and economic strong and weak points related to the full LC of this structural product. The LCA results show that the raw materials production is the LC phase with the higher environmental burden, *fossil fuels*, *respiratory inorganics* and *climate change* being the more relevant impact categories. The high impact of the production of raw materials is due mainly to the energy intensive process used in the manufacture of glass fibres. The LCC results evidence that the potential internal costs are the most significant ones, the tank manufacture and raw materials production being the more relevant contributors to the total cost. The study also showed that the environmental and economic performances of the composite tank would be improved if an EoL option distinct from deposition in landfill had been chosen.

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