USING A GLASS-FIBRE REINFORCED POLYMER COMPOSITE IN THE PRODUCTION OF SUSTAINABLE WATER STORAGE VESSELS

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ABSTRACT: The quest for sustainability by rethinking materials, products and production strategies is an enormous challenge currently laid upon the economic sector. Materials selection plays a critical role in this challenge. The present work describes a technological, environmental and economic study of the production of a water storage glass-fibre reinforced composite vessel. The vessel was evaluated via a Life Cycle Assessment/Life Cycle Costing (LCA/LCC) integrated model. The most significant life cycle phase was found to be the raw materials production, in which the *Fossil fuels*, *Respiratory inorganics* and *Climate change* were the relevant impact categories. The vessel environmental and economic performances could be improved if an end of life (EoL) option different from landfill had been chosen. The present work describes a new integrated way of analysing the environmental and economic performances of a structural product full life cycle. It also highlights the role and importance of fibre reinforced polymer composites in the quest for sustainable products.

1 INTRODUCTION

The quest for sustainability by rethinking products and production strategies is an enormous challenge currently laid upon the economic sector either by legislation or public opinion. Sustainable development includes environmental, economic and social aspects, known as the three pillars model (Klöpffer 2008). These three pillars have to be properly assessed and balanced when a new product or process is to be initiated or an existing one is to be improved. This should be the ultimate objective of product development (Klöpffer 2003, 2008).

As a consequence of the above, the integration of environmental and economic criteria with the traditional requirements in product design is gaining vital importance for many companies (Alves et al. 2009, Peças et al. 2009, Ribeiro et al. 2008, Simões et al. 2010, 2012a). It is well known that environmental impacts, as well as future cost and revenues of products, originate to a high extent in the design phase (Asiedu & Gu 1998, Hauschild et al. 2005, Rebitzer et al. 2003, Seo et al. 2002). The sustainable development approach uses several methods and tools, amongst them are Life Cycle Assessment (LCA) (ISO 2006a, 2006b) and Life Cycle Costing (LCC) (Ciroth et al. 2008, Swarr et al. 2011) that 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 one such approach allows recognizing and addressing 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 economic analysis, have already been integrated in product development processes, using different approaches (Allacker 2012, Bovea & Vidal 2004, Kicherer et al. 2007, Huo & Saito 2009, Nakano & Hirao 2011, Simões et al. 2012b).

Materials selection plays a critical role in this quest for sustainability. More than 160,000 materials are currently available to the engineer for the design and manufacturing of products for many (Ashby 2011). Polymers are increasingly replacing traditional materials such as metals, because they present a combination of properties which are more attractive to the engineer (e.g., light weight, corrosion resistance, versatility, etc). Additionally, the engineer can combine the best properties of polymers and other materials to make composites (Ashby & Jones 1996). Currently, composites are widely used in various products and industries, such as automotive components, sport and consumer goods, aerospace parts, and marine and oil industries components and equipment (Mazumdar 2002).

In this context, the present work aims at assessing the environmental performance and all costs involved in the full life cycle of a specific engineering product. This product is a vessel to store treated water before distribution (Bhardwaj 2001), made of glass-fibre reinforced polymer composite, for which two different end of life (EoL) scenarios are analysed: landfill and incineration with energy recovery. The overall goal of this study is to identify strong and weak points related to the life cycle of the vessel system. The results provide enlightening insights into the synergies existing between the environmental and economic performances.

2 METHODOLOGY

The LCA/LCC integrated framework adopted, which includes all stages of a product's life (Simões et al. 2012b), 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 the Life cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) results. 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 LIFE CYCLE ASSESSMENT

In this study, the focus was made on a commercial horizontal vessel to hold drinking water at atmospheric pressure. The vessel consists of a cylindrical body, and the corresponding top and bottom. 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 life cycle, were excluded from the analysis. A horizontal vessel with a holding capacity of 50 cubic meters was selected. The composite vessel, having a cylindrical shell and bottoms/accessories processed by filament winding and hand-lay-up, respectively, was designed according to BS 4994-1987 using as base material a fibreglass 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 vessel lifespan depends on the construction material and local weather conditions (e.g. salty sea air). The real lifespan of this product is not yet completely known. The manufacturer's experience is that it is longer than 30 years. In fact, they do not know of any case where it was necessary to substitute a vessel due to material damage in that period. Therefore, a 30 year lifespan was assumed in this work. Accordingly, a vessel with holding capacity of 50 cubic meters of drinking water at atmospheric pressure and a lifespan of 30 years was defined as the functional unit. The LCA is based in a "cradle-to-grave" assessment which considers the raw materials production, vessel production, on-site 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 life cycle phases are excluded from the study. It is supposed that at the end of its useful life the vessel this 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 analysed, since in some Portuguese regions it is possible to opt for this waste treatment option. The system was modelled using commercial databases (Buwal 250 database 1996, Ecoinvent database 2007, IDEMAT 2001 2001) and field data, which were ultimately summarized in the LCI performed in SimaPro 7 (PRé consultants 2011). The LCIA was carried out using the Eco-Indicator 99 (EI99) method (Goedkoop & Spriensma 2001). Figure 1 and Figure 2 present, on a functional unit basis, the relative characterization results of the vessel, excluding (Figure 1) and including (Figure 2) the EoL stage.

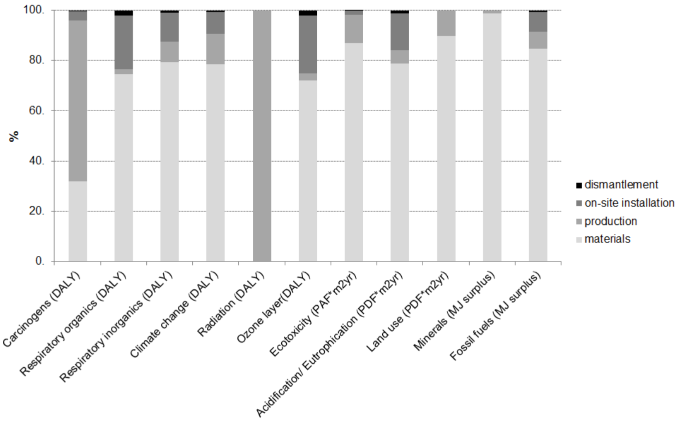

Figure 1. Characterization results of the vessel system, excluding the EoL stage. DALY: Disability Adjusted Life Years (years of disabled living or years of life lost due to the impacts); PAF: Potentially Affected Fraction (animals affected by the impacts); PDF: Potentially Disappeared Fraction (plant 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 1 reveals that the production of raw materials (glass-fibre reinforced polymer composite) has the highest emission values in all environmental categories, except in the *Carcinogens* and *Radiation*. In this case, the main contributor is the vessel production phase. The high impact of the raw materials production stage is mainly due to the energy intensive process used in the manufacture of glass fibres. The vessel 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*.

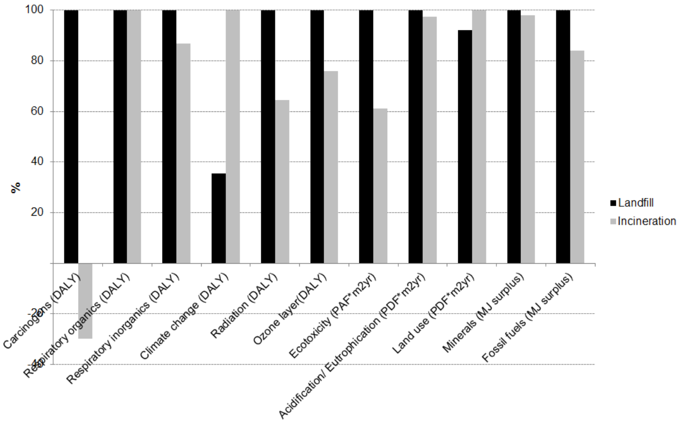

Figure 2. Characterization results of the vessel system, including the EoL stage.

Moreover, the incineration with energy recovery EoL scenario would decrease by 16% the Fossil fuels environmental impact category, due to the energy recovered from the burning of its matrix. Conversely, the *Climate change* environmental impact increases 64%. This is consistent with previous studies (Arena et al. 2003, Björklund & Finnveden 2005) that showed environmental savings in non-renewable resources (crude oil, natural gas and coal), as well as increases in greenhouse emissions, when applying this EoL treatment to waste plastics. The normalization results of the vessel for the two alternative EoL options are shown, on a functional unit basis, in Figure 3.

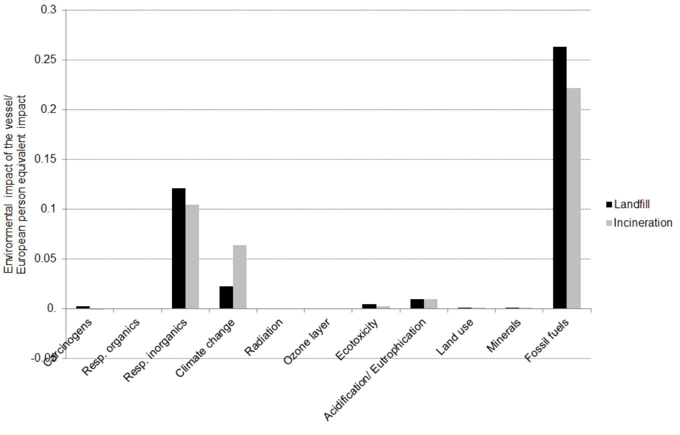

Figure 3. Normalization results of the vessel system, including the EoL stage.

Figure 3 shows that the *Fossil fuels*, *Respiratory inorganics* and *Climate change* categories represent the most significant burdens, in terms of scale of contribution in all systems.

4 LIFE CYCLE COSTING

In the integrated LCA/LCC model employed in the present work, the goal and scope of the LCC study for both vessel systems is consistent with the goal and scope of the LCA. Therefore the functional unit, system boundaries and other assumptions were the same as in both cases. In this way, the LCC methodology can be used to identify and compare all cost drivers associated with the two systems, based on a full life cycle perspective (producer perspective plus implications for market success due to use and disposal costs). The cost bearer “producer” is the company that manufactures the vessel. The final “user” of the vessel is the client that buys it. Ultimately, the “EoL” actor is the waste manager operator. The selected reference year was 2013, the discount rate used 3.5% and the LCC type a Societal LCC that considers internal and external economic aspects (Ciroth et al. 2008). Costs of CO_2 eq. emissions were accounted for, based on the carbon tax established by the EU ETS (Point Carbon 2012). The damage costs corresponding to the emissions of SO_2, NO_x and fine particles were accounted for, based on the ExternE project as adapted by NETCEN (Watkiss & Holland 2000). Due to confidentiality requirements the results shown in Table 1 are reported as “monetary units”. The vessel system depicts very different potential internal and external life cycle costs, the former being more than 99% of the total costs. The vessel production followed by the raw material cost is the main contributor to the total costs. The vessel system with incineration with energy recovery as EoL treatment shows a lower potential internal life cycle cost, due to the revenues that accrue from the sale of electricity.

Table 1. Internal, external and total costs of the vessel system for the two EoL treatment scenarios.

Life cycle stage	Costs (Monetary units/vessel system)		
	Total	Internal	External
Raw materials production	0.289	0.287	0.002
Vessel production	0.669	0.669	0.000
On-site 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

5 CONCLUSIONS

The present work describes the environmental and economic life cycle analysis of a glass-fibre reinforced polymer composite vessel, 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 life cycle of this structural product.

The LCA results show that the raw materials production is the life cycle phase with the more significant environmental burden, the *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 economic burdens, i the vessel production and raw material cost being the more relevant life cycle phases. The study also showed that the environmental and economic performances of the composite vessel would be improved if an end of life option distinct from deposition in landfill had been chosen.

The present work describes a new integrated way of analysing the environmental and economic performance of a structural product full life cycle. It also highlights the role and importance of fibre reinforced polymer composites in the quest for sustainable products.

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