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SUSTAINABILITY IMPROVEMENT OF A COMPOSITE MATERIALS' INDUSTRY THROUGH RECYCLING AND RE-ENGINEERING PROCESS APPROACHES

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ABSTRACT

This case study was aimed at measuring and assessing the potential improvements that could be made on the eco-efficiency performance of a composite materials' industry, specifically a glass fibre reinforced plastic (GFRP) pultrusion manufacturing company. For this purpose, all the issues involved in the pultrusion process of GFRP profiles were analysed, the current eco-efficiency performance of the company was determined, all the procedures applied in the production process were revised, and improvement strategies were planned and investigated with basis on the performed analysis. The new eco-efficiency ratios were estimated taking into account the implementation of new proceedings and procedures through re-engineering the manufacturing process and recycling approaches. These features lead to significant improvements on the sequent assessed eco-efficiency ratios, yielding to a more sustainable product and manufacturing process of pultruded GFRP profiles.

Keywords: sustainability, pultrusion industry, composite materials, waste recycling, eco-efficiency

INTRODUCTION

The sustainability of a business, company or industry is closely related to its eco-efficiency performance. Eco-efficiency is a management philosophy which encourages the companies to search for environmental improvements that also yields to parallel economic benefits. Its focus is on business opportunities allowing companies to become more environmentally responsible and more cost-effective. It drives innovation pushing growth and competitiveness. This concept of eco-efficiency was introduced for the first time at the end of last century by Schaltegger and Sturm (1989), and then launched and widely publicized by 'The World Business Council for Sustainable Development' (WBCSD) in Changing Course (Schmidheiny, 1992). As defined by this organization, '*eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity*' (Schmidheiny, 1992). The term was aimed at summing out, in a single expression, the business end of sustainable development: '*doing more with less'*, which means delivering more value using fewer resources.

However, making incremental efficiency improvements in existing practices and routines is not the single aim of eco-efficiency philosophy. It should stimulate creativity and innovation in the search for new ways of doing the same things. Further, eco-efficiency is not limited to the closest business areas such as manufacturing and plant management, but it also takes into account the activities upstream and downstream of a manufacturer's plant and involves the supply and product value-chains. As a result, eco-efficiency can emerge at any point in the entire life-cycle of a product and it is concerned with three broad objectives (Lehni, 2000):

- Reducing the consumption of resources – Minimizing the use of energy, materials, water and land, promoting recyclability and product durability, and closing materials loops -;
- Reducing environmental impact – Minimizing air emissions, water discharges, waste disposal and the dispersion of toxic substances -;
- Increasing product or service value – Providing more value to final consumer through additional product functionality, flexibility and/or modularity -.

Hence, implementing eco-efficiency in a company's business processes is first and foremost about navigating for opportunities and such opportunities can be found through four main approaches (Lehni, 2000):

- Re-engineering process approach – Re-engineering manufacturing processes in order to reduce the consumption of resources, reduce pollution and avoid risks, while at the same time saving costs - ;
- Recycling approach – Re-valorizing by-products and production wastes through cooperation with other companies, promoting recycling and the reuse of recyclates into new added value products; In endeavoring for zero-waste and 100% product targets, it has been found that the so-called waste from one processing industry can have value for another company-;
- Re-designing product approach – Re-designing products according to ecological design rules that leads to less environmental impact, higher rate of recyclability and disassemble facility-;
- Re-thinking market approach – Finding new ways of meeting consumer needs, working closely with the customers and related stakeholder groups to re-think the markets and re-shape demand and supply completely -.

In the present case study, the sustainability improvements that could be made in a composite materials industry were assessed by measuring the eco-efficiency performance of the company before and after the implementation of certain measures related to both re-engineering process and recycling approaches. A pultrusion manufacturing industry with headquarters in Maia, -ALTO, Perfis Pultrudidos Lda.-, was the subject of this case study and the analysis was restricted to the main business branch of this company: the production and selling of standard pultrusion glass fibre reinforced plastic (GFRP) profiles.

All the activities and procedures involved in the production process, as well as at upstream and downstream of manufacturer's plant were revised and analyzed, and improvement strategies were planned and investigated with basis on performed analysis.

METHODS

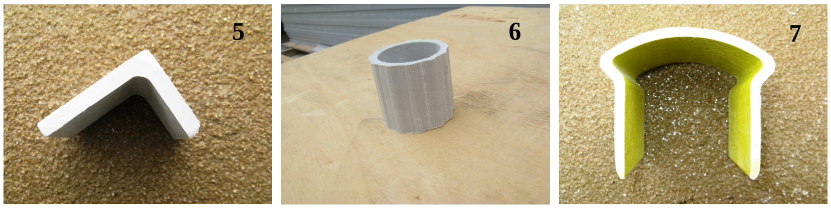
Measurement of Eco-Efficiency Performance

The quantification of eco-efficiency performance of company or business is a complex process that involves the measurement and control of several relevant parameters or indicators, globally applied to all companies (*generally applicable indicators*), or specific according to the nature and specificities of the business itself (*business specific indicators*).

The indicators fall into two main groups based on the eco-efficiency formula represented by the ratio of the two '*eco*' dimensions of economy and ecology relating product or service value to environmental influence. The generally applicable indicators for *product/service value* are: quantity of goods produced or quantity of services provided to costumers (i) and net sales (ii). Those relating to the *environmental influence in product/service creation* are linked to the consumption of energy (i), raw materials (ii) and water (iii), emission of greenhouse gases (iv) and ozone depleting substances (v). The business specific indicators are also discriminated according to its economic or ecological nature, but they are not global and must be individually defined from one business to another. A complete company's eco-efficient profile will include both types of indicators, value profile and environmental profile, and additionally, the eco-efficient ratios given by the previous two elements as 'numerator' and 'denominator' data.

In this particular study, the framework recommended by the WBCSD was adopted (Verfaille, 2000) and the guidelines of ISO 14301 standard (1999) were followed and applied. The main generally applicable indicators, as well as the business specific indicators, were defined and determined according to the above standard recommendations. With basis on indicators' figures, the value profile, the environmental profile and the pertinent eco-efficiency ratios were established an analysed. The analysis was restricted to the main business branch of the company: the production and sale of GFRP pultrusion profiles. The time-scale of the analysis was 75 working days and enclosed the production of seven different standard GFRP profiles illustrated in Fig. 1. The main inputs and outputs of the pultrusion production process of ALTO are specified in Table 1.

Profile W (100x14x3) **Profile U** (50x10x4) **Profile O** (9) **Profile L** (45x35x5)



Profile L (40x30x5) **Profile O** (31x3) **Profile Ω** (72x59/5 x4)

Fig. 1 Samples of the GFRP pultrusion profiles analysed in this case study (cross-section dimensions in mm)

Table 1. Main inputs and outputs of pultrusion manufacturing process of ALTO

Main INPUTS	**Main OUTPUTS**
Electric Energy	GFRP pultrusion profiles
Virgin Raw Materials:	Production wastes:
• Thermoset polyester resin;	• Non-conform profiles;
• Glass reinforcing fibres;	• By-products and manufacturing rejects;
• Calcium carbonate; pigments, catalyst system and other additives;	• Scrap material derived from cutting and assembly processes of GFRP profiles

According to the main inputs/outputs, four generally applicable indicators (for product value and environmental influence), and one business specific indicator of environmental influence were selected for eco-efficiency assessment. The specifications of each indicator are detailed in Table 2.

Table 2. Selected generally applicable and business specific indicators for eco-efficiency performance assessment

Generally Applied Indicators	**Category**	**Aspect/Unit**
Quantity of Product: Total amount of GFRP profiles sold	Product value	Mass / kg
Net sales: Total recorded sales less sales returns and allowances	Product value	Monetary / €
Energy Consumption: Total amount of electric energy consumed in pultrusion process	Environmental influence	Electric energy / kWh
Materials Consumption: Sum of weigh of all raw materials required for GFRP profile production: polyester resin, glass reinforcing fibres (roving, mat and veil), calcium carbonate, pigments, catalyst system and other additives	Environmental influence	Mass / kg
Business Specific Indicators		
Total Waste to Landfill: Total amount of production wastes for disposal (by-products, non-conform products and manufacturing rejects derived from cutting and assembly processes of GFRP profiles)	Environmental influence	Mass / kg

For each pair of ‘product value’ and ‘environmental influence’ indicators, the respective six eco-efficiency ratios were computed for the analyzed framework time (75 days). The same indicators and eco-efficient ratios were then predicted for an equivalent time period taking into account the implementation of improvement strategies.

After analyzing all the procedures involved in the production process of GFRP profiles, it was concluded that it would be possible to improve the sustainability and eco-efficiency ratios of the company by reducing the environmental influence indicators: energy consumption, materials consumption and total wastes to landfill. That can be possible taking action on two key fronts as described in the following two subchapters.

Re-Engineering Process Approach: Optimization of die heating system

In the pultrusion process implemented in the company (ALTO), dry glass reinforcing fibres are pulled through a thermoset polyester resin bath for impregnation, and after the wetting process, the reinforcement is allowed to enter into a heated forming die where it attains the cross-section shape of the die and cures. Finally, outside the die, the composite profile already consolidated is pulled by a continuous pulling system and then a cut-off saw cuts the profile at a desired length. A schematic representation of pultrusion process is presented in Fig. 2.

Typically, and also in this case, the die is heated by external planar heaters as the most common heating system in pultrusion processes. However, this type of external heating system leads to significant loss of heat to the surroundings of the die.

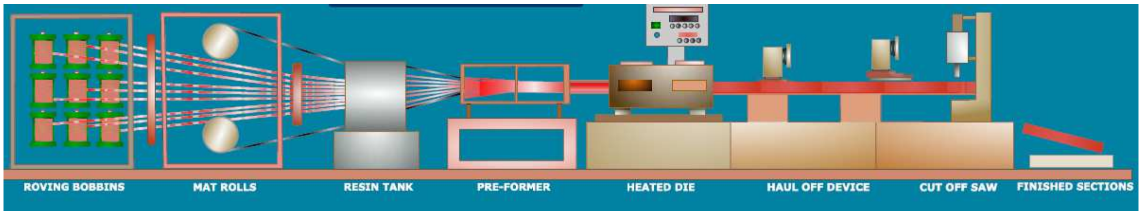


Fig. 2 Schematic diagram of pultrusion process

Earlier studies conducted by the authors showed that significant savings on energy consumption of pultrusion process could be achieved using embedded cylindrical heaters into the die instead of external planar resistances (Silva et al., 2012, 2013). Experiments were conducted in a 900 mm length die during the manufacturing process of a standard pultrusion profile (Profile U: 50x10x4) keeping all the other process parameters constant: pulling speed, pulling force, total resistance power and temperature profile (TP) along the die. These process parameters were already fine-tuned by the large experience of the manufacturer, and conduct to a high standard of quality of pultruded part. TP was first experimentally obtained by thermography techniques, for the external heating system, and then numerically simulated by finite element analysis (FEA). After validation of FEA simulation, energy consumption with internal heating system was estimated using the same technique. Obtained results showed that internal resistances enhance significantly the energetic performance of pultrusion process, leading to 57% decrease of energy dispended in die heating process, which represents a reduction of 17% of total energy consumed in the pultrusion process. The warm-up time is also reduced up to 50%, which reduces significantly the lead-time of each order and increases the production time. Moreover, in posterior studies it was also found that the optimized position of the internal heaters throughout the die can ever additionally reduce the energy consumption linked to the heating process in more 8%. More details of conducted research studies can be found in Silva et al. (2012, 2013).

2) Recycling Approach: Mechanical recycling of production waste and reuse of recyclates as raw materials for new added-value products or into a close-looping process

In the actual framework of the pultrusion sector and, in general, in that of the composite materials' industry, production wastes, non-conform and end-of-live products are usually landfilled due to their limited recycling ability even when thermoplastic-based products are considered (Halliwell, 2006). Currently, by-products, non-conform profiles and production wastes of ALTO are also landfilled (Fig. 3), with sequent negative environmental impacts and supplementary added costs to this company. Wastes to landfill constitute around 7% of total annual production of 40 ton and lead to an estimated cost for the company of 4 M€ per year. However, mechanical recycling of GFRP waste materials, with reduction to powdered and fibrous particulates (Fig. 3), constitutes a recycling process that can be easily attained on heavy-duty cutting mills. The posterior reuse of obtained recyclates, either into a close-looping process, as calcium carbonate replacement for resin matrix of GFRP profiles, (which represents in average to 20% in weight of total raw materials applied in the manufacturing process), or as reinforcement into new composite materials, will drive to both costs reduction in raw materials and landfill process, and minimization of waste landfill.

Mechanically recycled GFRP wastes remain, however, mired by the scarceness of cost-effective end-use applications and clear developed recycling routes (logistics, infrastructures and recycling facilities) between waste producers and potential consumers for the recyclates.

Fig. 3 Typical wastes of GFRP pultrusion process (left) and samples of obtained recyclates after mechanical recycling in a heavy-duty cutting mill using different sized-meshes inside the grinding chamber (right).

Presently, new end-markets with added value for the GFRP recyclates are required. Regarding this subject, over the last 20 years several end-use applications were envisioned and investigated for mechanically recycled thermoset GFRP wastes or recovered glass fibre wastes (Pickering 2006). The most extensive research work in this field has been carried out on Portland cement concrete in which mechanically recycled GFRP wastes, and more rarely CFRP (carbon fibre reinforced plastic) wastes, have been incorporated either as reinforcement, aggregate or filler replacement. A brief state of the art on this matter can be found on Ribeiro et al. (2015). However, most of the times, this kind of end-use application of GFRP recyclates bring some undesirable features such as significant drop in the mechanical properties (mainly due to the high water-cement ratio required to achieve the desirable workability), higher wear loss and weak adhesion at recyclate-binder interface. Additionally, depending upon glass fibre nature, some incompatibility issues resultant from alkalis-silica reaction were also noticed. These limitations, by and large resultant from the use of a cementitious binder as matrix, might be avoided using a cementless concrete as host material for the recyclates, such as concrete-polymer composite materials.

Previous and impending experimental work carried out by the present research team (Ribeiro et al., 2013, 2015; Castro et al., 2013, 2014) show that GFRP recyclates can be successfully incorporated into polymer based concrete materials as reinforcement and partial replacement of aggregate components, leading to both flexural and compressive strengths increase of modified concrete materials. Replacement amounts up to 15% in weight are viable and cost-effective. Larger replacement amounts are also technological possible but lead to progressive drops on mechanical strengths of final product.

Obtained results highlight a viable technological option for improving the quality of GFRP filled polymer concrete materials, thus opening a door to selective recycling of GFRP waste. It is expected that around 80% of actual production waste of ALTO, corresponding to non-conform profiles and scrap material derived from cutting processes, can be mechanically recycled and reduced to fibrous/filler material, and posteriorly reused either as reinforcement for polymer based concrete materials or as partial calcium carbonate replacement of resin matrix in the pultrusion process, into a close-looping process.

RESULTS

Current and predicted value and environmental indicators

Measured value indicators are presented in Fig. 4, and in Fig. 5, the measured and predicted environmental indicators are depicted. Presented values are discriminated according to the 7 types of pultrusion profiles produced by the company during the framework time. They include the generally applicable four value and environmental indicators and one business-specific indicator of environmental influence (total of production waste and by-products to landfill).

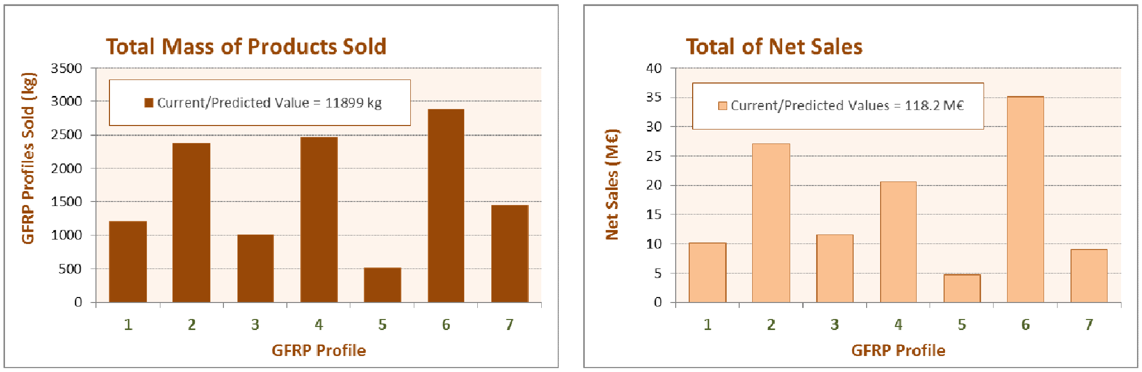


Fig. 4. Value indicators according to the GFRP profile type produced by the company

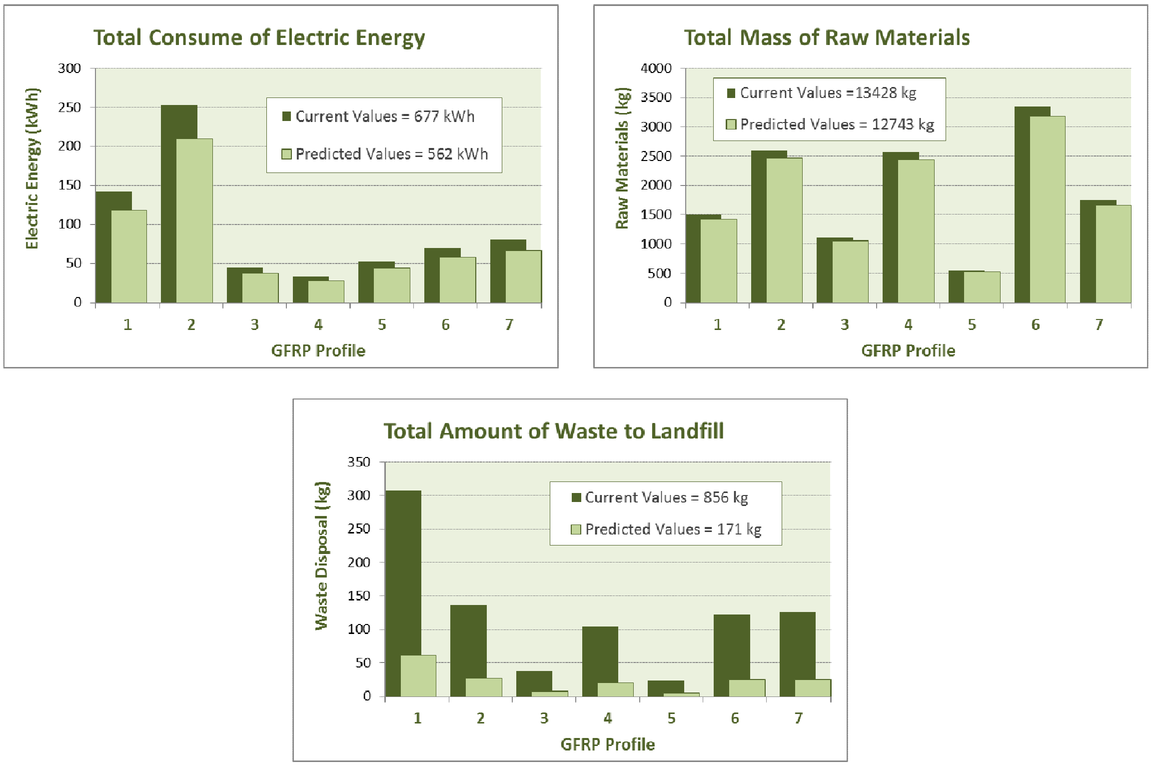


Fig. 5 Current and predicted environmental influence indicators according to the GFRP profile type produced by the company

For the prediction of the new environmental influence indicators the following assumptions were assumed:

- The replacement of the die heating system (external planar resistances by internal cylindrical heaters) leads to 17% saving on the total consume of electric energy due to pultrusion process, irrespectively of the type of die/GFRP profile production;
- The savings on electric energy due to the optimization of heaters position along the die is not taken into account;
- The reduction on warm-up periods of the die, at the beginning of each run/order, is disregarded and it is not reflected in an eventual increase of production rate (the value indicators were kept equal);
- 80% of the current amount of production waste to landfill is able to be mechanically recycled;
- 25% of the total amount of calcium carbonate applied in the production process of GFRP profiles is the maximum amount that could be replaced by fine-ground GFRP recyclates into a close-looping process.

Current and predicted eco-efficient ratios

With basis on the above indicators, current eco-efficient ratios were determined and compared with those that could be obtained implementing the improvement strategy approaches. Obtained results are presented in Table 3.

Table 3 Actual and predicted Eco-Efficiency Ratios (EER)

Mass of product sold per:	**Energy consumption**	**Materials consumption**	**Total waste disposal**
• Actual EER	17.58 kg/kWh	0.89 kg/kg	13.91 kg/kg
• Expected EER	21.17 kg/kWh	0.93 kg/kg	69.58 kg/kg
Net sales per:	**Energy consumption**	**Materials consumption**	**Total waste disposal**
• Actual EER	174.59 €/kWh	8.80 €/kg	138.08 €/kg
• Expected EER	210.32 €/kWh	9.28 €/kg	691.22 €/kg

CONCLUSION

The implementation of a new die heating system and, especially, mechanical recycling approach, with partial waste reuse of scrap material derived from manufacturing, cutting and assembly processes of GFRP profiles, will drive to both minimization of waste disposal and cost reduction on raw materials, electric energy and landfill process. These features lead to significant improvements on the sequent assessed eco-efficiency ratios of the present composite materials' industry, yielding to a more sustainable product and manufacturing process of pultruded GFRP profiles.

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