Life Cycle Assessment (LCA) combined with EMergy evaluation for a better understanding of the environmental aspects associated with a crystal glass supply chain

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Abstract

Life Cycle Assessment (LCA) has gained wider acceptance as a quantitative environmental performance tool, based on mass and energy balances. This paper applies the LCA method in a combined form with Emergy, which is a holistic and thermodynamic tool for the physical evaluation of environmental resources and services. A crystal glass production has been assessed as a case study. According with LCA method, the system was analysed from "cradle to gate". Data elaborated refer to 1 kg of crystal glass packed (functional unit). Results of life cycle inventory and impact assessment showed the highest contribution of the manufacturing phase to the total environmental impact, with evidence of CO_2, NO_x, SO_2, and heavy metals emissions and some acid wastewater releases. Emergy results have been useful for carrying out a more reliable evaluation of the non-renewable resources involved, in terms of solar energy needed for generating 1 kg of crystal glass (sej/kg). Also with emergy analysis, the manufacturing phase highlighted the highest resources exploitation, due to water and natural gas uses. The combined use of emergy and LCA contributes important information useful for the comprehension of the crystal glass system organization and its level of environmental pressure, which could be reduced. Moreover, the integration may provide a base for a future development of the emergy evaluation within an LCA framework.

Keywords: cradle to gate, crystal glass, emergy evaluation, environmental standards, life cycle assessment (LCA), sustainability, sustainable indicator.

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1 Introduction

In Italy, like most countries in Europe, eco-efficiency initiatives are primarily based on a voluntary approach. Companies which implement eco-efficient practices will be able to better respond to competitive pressures, anticipate customer needs, protect the environment, and enhance their reputation and trust by demonstrating the careful and responsible actions of their businesses [1]. Relating to manufacturing processes, environmental problems could be critical in the production of glassware and ornamental articles made of lead crystal, which requires a more stringent compliance with the requirements for decreasing toxic emissions into the air, as well as the discharge of contaminating agents into water reservoirs from the recycling of acid wastes [2]. Lead crystal, crystal glass or simply crystal, is the term used to describe a glass composition used for hand or machine based production of more decorated glass items. According to an EU directive [3], glass traded within the EU must contain more than 24% PbO to be called ‘crystal’. Moderate additions of PbO into glass increase chemical resistance and lower the melting temperature resulting in decreased hardness, but an increased refractive index, which is important for its ‘brilliance’.

Aim of this work was to provide a sustainability evaluation of a crystal glass production. The analysis focused on the assessment of impacts derived from inputs and outputs use (LCA), integrated with a physical evaluation of the resources and natural services (EMergy). In fact, the Life Cycle Assessment (LCA) method [4] is a useful analytical tool for providing environmental profiles in productive processes of different kinds. Studying the crystal life cycle enabled us: a) to identify its weak points and critical aspects (processes with the highest emissions, and material and energy consumptions); b) to suggest technical improvements for reducing its potential and/or actual environmental impact; c) to define an environmental profile of the crystal glass productive system. Emergy evaluation [5], on the other side, deals at best with systems at the interface between the ‘‘natural’’ and the ‘‘human’’ spheres [6], and it is able to account for all the inputs on a common basis; i.e., the solar energy. So, the joint use of the methods provided important elements and information useful for the comprehension of the organization of the crystal productive system, and the use of the energy flows that determine its development.

2 Materials and methods

2.1 Life cycle assessment

The Life Cycle Assessment (LCA) is a versatile tool for quantifying the overall environmental impact from a product, process, or service. An LCA may include all the production processes and services associated with a product through its life cycle, from the extraction of raw materials through production of the materials used in the manufacture of the product, over the use of the product, to its recycling and/or ultimate disposal of some of its constituents. Such a complete life cycle is also named “cradle to grave”. Transportation, storage, retail, and other activities between the life cycle stages are included where relevant. In this life cycle assessment, use of the crystal glass and end-of-life treatment were not included. This is the case of a "from cradle to gate" LCA. In Figure 1, the main phases and sub-processes that occur during the productive chain are presented.

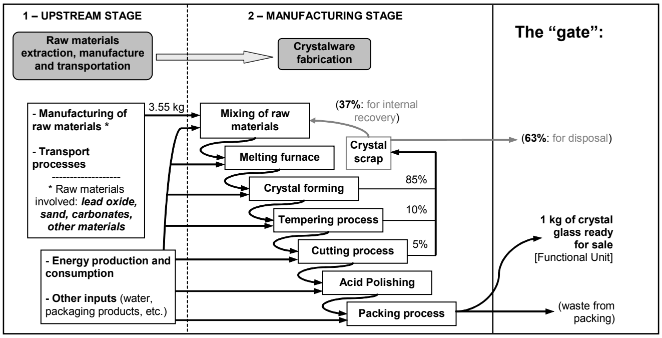

Figure 1: Model of the crystal glass life cycle from "cradle to gate".

A framework for LCA has been standardised by the International Organisation for Standardisation (ISO) in the ISO 14040-44 series. A typical LCA-study consists of the following stages: 1) goal and scope definition; 2) life cycle inventory (LCI); 3) life cycle impact assessment (LCIA); 4) interpretation and improvement. For a deeper description of the rules and methodological aspects related to LCA, please refer to Baldo et al. [4]. Once the functional unit, boundaries of the system, requirements for data, limitations and assumptions of the study were fixed by following the rules of stage 1 above, we accounted the emissions that occurred, and the raw materials and energy that were used during the life-cycle of the crystal glass production (stage 2). Subsequently, an assessment of the potential impact related to these emissions was made, providing an environmental profile of crystal glass products by using some specific characterization factors (stage 3). Finally, we tried to interpret the results of the impact assessment in order to suggest technical improvements for reducing environmental burdens (stage 4). In order to account for indirect emissions and consumptions we used EDIP database and GaBi4 software, which are specific tools for LCA studies. The former enabled to complete the LCA data collection, the latter to combine the various input and output flows in each unit process of the life cycle model.

2.2 Emergy evaluation

Emergy converts all forms of energy and materials into equivalents of one form of energy: in fact, inputs to a process are normalized to a common unit, namely the *solar emergy joule* or *solar emjoule* (sej). Based on this unit, emergy is defined as the quantity of solar energy that was used, directly or indirectly, to obtain a final product or service, or to support a given system and its level of organization [5]. So, because solar energy is the primary source that feeds all processes and cycles that are found on Earth, emergy is a sort of memory of the solar energy [7]. In Figure 2, the emergy system diagram is represented. The ratio of the total emergy used to the energy of the product gives a unit emergy value, namely transformity or specific emergy, in units sej/J or sej/g, respectively. Transformities can be used to “convert” a given product into emergy, by the fact that mass quantities (g) or energy quantities (J) of each input flow are multiplied by the related transformity, giving its emergy content (sej). Moreover, transformity can be conceived as an indicator that represents the position of a given transformation process (and its product) in the hierarchical network of the earth's biosphere [5]. When comparing two or more processes with the same output, a lower transformity is a measure of higher efficiency, i.e., more product obtained with a given quantity of emergy, or less emergy needed to produce a given amount of product. In the present paper, the values of the transformities are taken from previously published studies and through them, we performed an evaluation of the emergy required for each input flow, and from the sum of the calculated emergy values, the total emergy of the production was obtained. For obtaining the specific emergy (transformity) of the crystal glass, the total emergy was divided for 103.72 tonnes, which was the production capacity of the plant we studied during the year 2007.

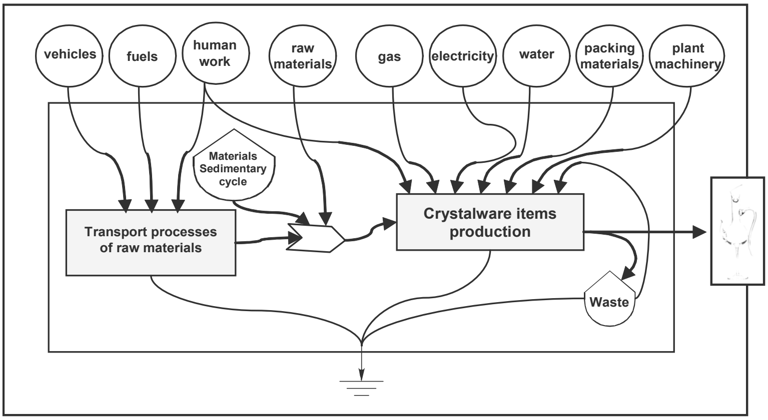

Figure 2: Emergy system diagram of the crystal glass production.

2.3 Case study and boundaries of the system

The area of Colle Val d'Elsa, Siena (Italy), is an important site for the crystal glass traditional manufacturing. It has achieved a production of 95% of crystal nowadays produced in Italy, i.e. 15% of the world crystal production. In general, the 55% of this 95% is intended for export. The case study presented here is representative of a small-medium company, closer to a handmade enterprise than to a real industrial system, which is usually more interested in quality than quantity of products. The company has an average production of 100 tonnes/year of crystalware goods, which are distributed in Italy (about 75% of the products) and exported worldwide (about 25%). It follows a traditional manufacturing way, where each product is hand-made by expert master craftsmen. Twenty-two people are employed in this company, which follow the entire manufacturing chain from the mixing of raw materials to the packaging of the final product. Raw materials (e.g., sand, lead oxide) and other commodities (e.g., energy carriers, pot clay) are produced elsewhere, in Italy or in Europe (i.e., sand).

A cradle-to-gate analysis (from extraction of raw materials to the distribution of the final packed product) has been conducted: a quantity of 1 kilogram of crystal (ready for sale) was chosen as functional unit (see Figure 1). The crystal-glass life cycle was divided in two main phases: 1) raw materials acquisition (upstream stage), and 2) crystal glass products fabrication (manufacturing stage). The first stage of raw materials acquisition includes all the activities required for gathering and manufacturing raw materials and fuels. This stage also includes the process of transport of raw materials to the industrial plant. The second stage includes the production processes that take place within the industrial plant: a) mixing of raw materials, b) melting furnace, c) crystal forming, d) tempering processes, e) cutting processes, f) acid polishing, and g) packing. The manufacturing stage also included a recovery of crystalware defective pieces from the sub-processes “c”, ”d” and “e” that, once rejected and scrapped, are re-used in the mixing of raw materials without undergoing chemical transformations. In emergy analysis this consists in a “feedback” flow. Rejected materials are usually a relevant quantity, due to the high quality of crystal products, which imposes to scrap all the items with a physical defect or refractory impurities after crystal forming or handling.

3 Results and discussion

3.1 Life cycle assessment

LCI results for input balance have shown that the energy consumption is higher during the manufacturing stage (Figure 3). This is due primarily to the consumption of non-renewable energy resources (crude oil, hard coal, lignite, natural gas) during the life cycle, with natural gas being the major fossil fuel exploited in two sub-processes of the second stage: melting and forming processes (about 40% and 16% of total life cycle energy consumption, respectively). Moreover, a large volume of water usage was detected, mainly during the sub-processes of cutting and acid polishing (around 10 kg and 3 kg per functional unit, respectively). Regarding emissions, a balance result on output flows was also performed: it has been observed that the manufacturing stage was still the phase where values in outputs were the highest, especially for those regarding air and water emissions. The major contribution was due to CO_2 emitted during the sub-process of melting in the furnace. To assess the potential impact due to the emissions accounted with LCI, four category indicators were selected from CML2001 impact categories [8]: Acidification Potential (AP);

Eutrophication Potential (EP); Global Warming Potential (GWP); Ozone Layer Depletion Potential (ODP). The contribution (in absolute values) of each total potential impact is listed in Table 1, which holds absolute values of the characterization of LCIA. The manufacturing stage had the greatest contribution to all the impact categories selected, especially for that regarding global warming potential. The other stage showed a lower contribution of potential effects, nearly negligible, compared to manufacturing.

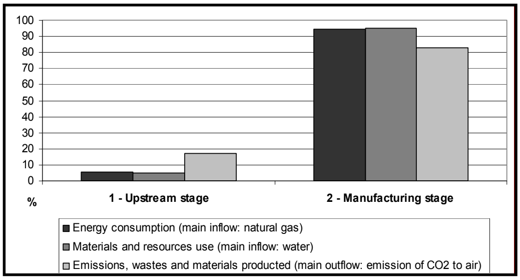

Figure 3: Profile of the life cycle inventory: contribution of energy consumptions (input flows), resources and products/materials utilization (input flows) and emissions (output flows) involved in the crystal glass production.

The CML method was applied to the balance of the system, adapting the normalisation to the CML Western Europe factors [8]. According to this normalisation, it was confirmed that the largest environmental problems may be associated with the manufacturing phase, which kept the higher potential impact for GWP, AP and EP. Only for ODP, which however revealed a very low potential impact compared with the other indicators, we found a more consistent contribution of the upstream stage. Since the manufacturing stage recorded the highest levels for each environmental impact considered, this phase was assessed in detail to identify "weak points" for each category, and to determine which sub-processes of the manufacturing were more significant in terms of environmental burden.

Table 1: Absolute values (per functional unit) of the characterization.

Impact category indicator and acronym (from CML 2001 method)	**Unit**	**1 Upstream stage**	**2 Manufact. stage**
Acidification Potential, AP	[kg SO_2-Equiv.]	1.04E-02	1.09E-01
Eutrophication Potential, EP	[kg PO_4-Equiv.]	7.11E-04	7.19E-03
Global Warming Potential, GWP	[kg CO_2-Equiv.]	1.12E+00	2.05E+01
Ozone Layer Depletion Potential, ODP	[kg R11-Equiv.]	4.22E-08	7.68E-08

The process of melting in the furnace, which makes use of a large quantity of natural gas, revealed the highest contributions to GWP and EP (43.45% and 41.27%, respectively), while the polishing contributed mainly to AP and ODP

(39.23% and 56.04%, respectively). This was due to the usage of acids during the cleaning of crystalware – i.e., hydrogen fluoride and sulphuric acid –from which derive waste waters to be treated before their re-introduction in the sewage system.

3.2 Emergy evaluation

Raw inputs of the crystal production and relative calculated emergy flows are shown in Table 2. The emergy requirement of the total crystal production during one year (for 103.72 t) was $2.55 \cdot 10^{18}$ sej, while the specific emergy of the crystal glass was $2.46 \cdot 10^{10}$ sej/g of product. This can be a reference value for future comparison of system efficiency. For instance, Buranakarn [14] has already provided a specific emergy for the common glass, which is $2.16 \cdot 10^{9}$ sej/g.

Table 2: Raw inputs and emergy evaluation of the crystal glass system under study (inputs are for 103,72 tonnes/year crystal production).

Items	Unit	Input	Solar *Tr* (sej/unit)	*Em* flow (sej/t/yr)	Ref. for *Tr*
Inputs					
1 Vehicles (per km)	g·km	1.01E+12	9.19E+04	9.27E+16	[9]
Raw materials:					
2 Sand	g	1.48E+08	1.00E+09	1.48E+17	[5]
3 Lead oxide	g	7.40E+07	1.00E+09	7.40E+16	[5]
4 Carbonates	g	6.19E+07	2.20E+09	1.36E+17	[12]
5 Oxides	g	7.00E+05	2.56E+09	1.79E+15	[5]
6 Other compounds	g	3.20E+06	1.00E+09	3.20E+15	[5]
Energy inputs:					
7 Gas	J	2.01E+13	4.00E+04	8.04E+17	[10]
8 Electricity	J	1.31E+12	1.85E+05	2.43E+17	[13]
Plant machinery and building:					
9 Machinery	g	4.08E+07	6.70E+09	2.73E+17	[14]
10 Building	m^3	4.00E+04	1.07E+11	4.28E+15	[15]
Packing materials:					
11 Pallets	g	3.40E+05	2.40E+09	8.16E+14	[14]
12 Polyurethane	g	9.26E+05	8.85E+09	8.20E+15	[14]
13 Plastic	g	5.91E+06	8.85E+09	5.23E+16	[14]
14 Cardboard/carton	g	3.94E+07	3.90E+09	1.54E+17	[12]
Other materials for manufacturing:					
15 Refractory (pot clay/furnaces)	g	5.55E+06	2.00E+09	1.11E+16	[5]
16 Oxygen	g	1.10E+07	5.16E+07	5.69E+14	[17]
17 Hydrogen fluoride	g	1.16E+07	3.80E+08	4.41E+15	[11]
18 Sulphuric acid	g	4.89E+07	3.80E+08	1.86E+16	[11]
19 Water input	g	2.67E+11	1.95E+06	5.22E+17	[16]
20 Human labour	J	1.58E+07	1.24E+07	1.95E+14	[11]
21 Re-usable crystal glass	g	8.02E+07	2.46E+10	1.97E+18	
Output (product)					
22 Crystal glass	g	1.04E+08	-	-	-
23 Emergy of Crystal glass	sej	-	-	2.55E+18	-
24 Specific Emergy of Crystal Glass	sej/g	-	2.46E+10		-

Although the two productions (crystal-glass vs. common glass) should be more deeply investigated (especially for finding possible lack of conformity), the discrepancy of the two specific emergy values may enable to argue that the glass production analysed by Buranakarn is more efficient than the crystal glass production studied here. Then, a deeper investigation is necessary to understand for possible reasons of this finding. Results occurred from the emergy evaluation allowed us to consider that: a) the highest contribution (in emergy terms) was due to the gas consumption (32% of the resources involved); b) an important direct contribution was due to the local resources exploitation and usage, in which water had the highest term (22% of the total involved resources); c) the manufacturing phase represented the significant step in emergy terms, because involved all the main emergy flows accounted for (i.e., gas, water, machineries and electricity); d) a very high percentage of the total emergy was represented by the re-usable crystal glass volume (77% in emergy terms), which however cannot be considered as a direct emergy input flow because is a feedback (see section 2.3). For a rule of emergy algebra, these kinds of flows cannot be double counted [5].

3.3 Discussion

Similar results came out from the application of the two methods, even if emergy could consider the local contribution of added inputs such as human labour and plant machineries. These inputs were almost negligible compared with the contribution of the gas usage. From the results, it is clear how the manufacturing stage has prevailed over the upstream stage in terms of emissions and consumption of resources. It is difficult, however, to determine the relative size of the potential impacts calculated, since this is the first life-cycle analysis performed on crystal glass production, and therefore the indices of the effects considered do not permit a comparison with any similar data in literature. However, the results obtained have been helpful to producers to determine on which processes it is necessary to focus more attention. That is, those manufacturing sub-processes, especially the melting process in the furnace, for which a direct responsibility of the company exists, and on which the company could make interventions to reduce emissions and/or consumption. The processes of forming, cutting and acid polishing are also responsible for most of the emissions. In fact, they were all phases of crystal processing that required the use of industrial technologies. However, for a process such as mixing, which presented the highest exploitation of non-renewable resources (e.g., mineral resources), we can talk about indirect responsibility of the company, since consumption during extraction and manufacturing of raw materials occurs outside of the company. A major investment in local resources is necessary to decrease the impact of transportation processes, which however has been lower than that caused by the energy consumption – i.e., electricity and gas. Furnaces for melting raw materials mixture in the industrial plant need to be continuously (24 hours) kept at a high temperature of 1200/1300°C. However, technological improvements would have positive effects for saving energy; for example, heat recovery furnaces would enable energy internal recycling or renewable energy resources, such as bio-fuels, would represent an alternative to the use of natural gas. The replacement of natural gas, theoretically, may allow a net reduction of emissions from combustion to feed furnaces directly, and from the extraction, refining and distribution processes of natural gas indirectly. Nevertheless, despite high emissions, the need of continuous processes in high temperature furnaces and raw materials acquisition cannot be easily modified if we want to guarantee the production of high quality hand-crafted products, based on such a traditional method of manufacturing.

4 Conclusions

Results of LCI were useful to support an assessment of potential impacts for both emissions (by using LCIA) and (solar) energy consumptions (by using Emergy) occurred during the crystal supply chain. The integration of the two methods confirmed how LCA can be a valid method for providing a systematic and detailed quantification of all input-output flows that occur in a system. When these flows are then used for an emergy evaluation, this can supply an added systemic and synthesised view of the system functions. The complementarities of the two methods were useful to provide a full comprehension of the system organization, highlighting how the crystal glass manufacturing depends upon a high use of non-renewable resources, principally based on natural gas demand. It was difficult to define a relative sustainability level for this production, since we could not compare our results with those of a reference study or value. At present state, we cannot argue that the crystal-glass manufacturing we studied may be an example of “sustainable production” in each sense. However, a reduction of the actual environmental burdens identified by the “weak point analysis” is possible, through the application of some technological solutions to improve the environmental performance of the sub-processes found critical. This may certainly help crystalware productions to move closer to a better state of environmental sustainability.

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