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VALORIZATION OF MUSSEL SHELL FOR ITS USE AS AN AGGREGATE IN UNBOUND APPLICATIONS: LIFE-CYCLE SUSTAINABILITY INDICATORS.

Bordello Malde, Lucía; de la Cruz López, M. Pilar; del Caño Gochi, Alfredo Universidade da Coruña

Canneries produce large amounts of mussel shell waste. In addition to the extra cost of its management, this waste can cause a significant environmental impact. This is a major problem in Galicia (Spain), one of the world's largest producers. Other countries like Chile and Korea have similar problems with a variety of bivalve waste. Mussel shell from the canning industry can be transformed into a valuable byproduct, by recycling it as granular material for construction applications. Elimination of organic matter and grinding or milling are required steps for the raw waste to be used as a recycled material. The construction system to which the shell is incorporated will set the specifics of these treatments. The objective of this paper is to analyze the life cycle associated with the valorization of mussel shell for its use as aggregate in the construction sector. The focus is put on its use in unbound applications such as filling material in thermal and acoustic insulation, or correction of gravel in road surfaces. A set of environmental, social and economic indicators that allows the sustainability assessment of these construction systems is also presented.

Keywords: *mussel shell; valorization; sustainability; thermal insulation; acoustic insulation; gravel*

VALORIZACIÓN DE LA CONCHA DE MEJILLÓN COMO AGREGADO EN APLICACIONES NO LIGADAS: INDICADORES DE SOSTENIBILIDAD EN EL CICLO DE VIDA.

Las empresas conserveras producen grandes cantidades de residuo de concha de mejillón. Además del sobrecoste de su gestión, este residuo puede llegar a provocar un importante impacto ambiental. Este es un problema especialmente importante en Galicia (España), que es uno de los mayores productores mundiales. Otros países como Chile o Corea tienen problemas similares con bivalvos de diverso tipo. La concha de mejillón procedente de la industria conservera necesita ciertos tratamientos para poder ser empleada como material granular en aplicaciones constructivas, convirtiéndose así en un subproducto. Estos tratamientos se centran en la eliminación de la materia orgánica y en la trituración o molienda, según las exigencias del material o solución constructiva a la que se incorpore la concha. El propósito de esta comunicación es analizar el ciclo de vida asociado a la valorización de la concha de mejillón para su uso como árido en el sector de la construcción. En concreto, se plantea su uso en aplicaciones no ligadas, tales como material de relleno para aislantes térmicos y acústicos, o corrección de zahorra para firmes de carretera. Se presentará una serie de indicadores ambientales, sociales y económicos para la evaluación de la sostenibilidad de estos sistemas constructivos.

Palabras clave: *concha de mejillón; valorización; sostenibilidad; aislamiento térmico; aislamiento acústico; zahorra*

Correspondencia: Alfredo del Caño Gochi alfredo@udc.es

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1. Introduction

Galicia (North-West of Spain) is one of the largest bivalves' producers in the world, and the European leader in the production and export of canned mussels. According to *Consellería do Medio Rural e do Mar* (2012), this industry produces 200,000 t (metric tons) per year of this bivalve and, consequently, more than 80,000 t of mussel shell (hereinafter MS). This waste accumulates in poorly equipped areas, creating an undesirable visual and olfactory effect, with serious damage to environment and tourism.

Recent regulations and strategies on waste (European Commission, 2005; European Union, 2006) open new opportunities for sustainable development, through the management and treatment of waste from aquaculture. They encourage not only the application of environmental technologies, but also the recycling of waste and its possible use as by-product.

Recently, the possibility of adding waste material to non-structural building solutions was investigated. In the United Kingdom scallop shells have been used in the construction of forest ways (Scottish Environment Protection Agency, 2005). In The United States, MS has been recycled as a soil conditioner and fertilizer for the agricultural soils (Cline, McKenna, 1996). In South Korea, Yang et al. (2005) studied the effect of crushed oyster shell as partial replacement of sand in concrete. In Spain, there have been several research projects about the use of bivalve shells with the aim of finding alternatives to the expensive waste management (Barros et al., 2009; Ballester et al., 2007). In many cases, some advantages have been tested, since some of the added binders improve mechanical characteristics against conventional alternatives. However, only mechanical and chemical properties were analyzed. Furthermore there is insufficient research about the contribution of these recycled materials to sustainability.

Even so, most of the produced shells are still not processed. The enormous amount of waste produced by the canning industry must find a niche market. Its use as construction material is a potential solution, since large volumes of material are consumed in this sector. The construction industry is one of the most pollutants, being responsible for 50% of natural resources consumption, 40% of the consumed energy and 50% of total waste generated (Anink, Mak & Boonstra, 1996). Therefore, it has great saving potential for reducing emissions and resource consumption.

For construction applications, MS needs a heating treatment, in order to remove organic matter; then, depending on its application, the MS could need specific milling processes. Iribarren, Moreira & Feijoo (2010) have conducted a research about MS life cycle valorization to produce calcium carbonate (Iribarren, 2010), analyzing specific environmental indicators. The processes for producing calcium carbonate are more demanding and aggressive with the environment than the necessary ones for the uses presented in this paper.

Up to date, there are numerous definitions of sustainable development, depending on the approach. It is commonly accepted the one introduced by the United Nations in the Brundtland Report (United Nations, 1987). This document establishes that sustainable development is the one that "meets the needs of the present without compromising the ability of future generations to meet their own needs". In turn, as the Declaration of Río on Environment and Development (United Nations, 1992) gathered, human beings "are entitled to a healthy and productive life in harmony with nature". This means the consideration of three sustainability pillars or dimensions: environmental, social and economic.

Construction industry is already involved in activities in relation to sustainability. There is a lively action aimed at the development of sustainability indicators. In the UK, a framework for sustainability indicators has been developed, specifically for metallic, construction and industrial minerals (Azapagic, 2004). In China, a work identifies thirty key indicators affecting the overall effectiveness of construction and demolition waste management (Yuan, 2013). In Spain, the Structural Concrete Code EHE-08 includes a model for assessing sustainability of structural concrete (*Ministerio de la Presidencia*, 2008).

This general framework is also appropriate for MS valorization. However, the work on indicators is still in its infancy and requires further efforts.

2. Objectives

The first objective of this paper is to analyze the emissions and energy consumption life-cycle associated with MS valorization. For that purpose, the necessary processes on the shell for its use as aggregate in unbound applications are studied.

On the other hand, this study aims proposing a comprehensive set of indicators to assess the sustainability of construction solutions that incorporate bivalve shells from the canning industry. Social, environmental and economic aspects are taken into account. The framework is suitable for sustainability reporting as well as internal use by construction companies. The indicators' set will serve to analyze the improvements produced by recycled materials against conventional solutions.

3. Life Cycle Assessment of MS Valorization: Emissions and Energy.

Life Cycle Assessment (LCA) is a useful tool for evaluating the environmental performance of a product or process by using an integrated approach that takes into account the product life cycle (Lozano et al., 2009).

3.1 Data Information

In Galicia, the industry currently managing MS focuses its activity towards agricultural and livestock sectors, being its facilities adapted to the demands of those sectors. This fact, added to the inability to access industry reports of consumptions and emissions, makes unviable achieving real data. As a result, the study by Iribarren (2010) has been taken as a starting point. In it, LCA methodology is used to assess the production of calcium carbonate ($CaCO_3$) from MS.

Unlike the case of obtaining $CaCO_3$, MS waste need less demanding treatments for the applications considered in this paper. These treatments are focused on the elimination of organic matter and subsequent milling, according to the requirements of the construction solution to which the shell is incorporated.

3.2 Boundaries and Functional Unit

The LCA will be a cradle-gate analysis. Such assessments are often the basis for Environmental Product Declarations (EPD) (Erlandsson, Lindfords & Ryding, 2005).

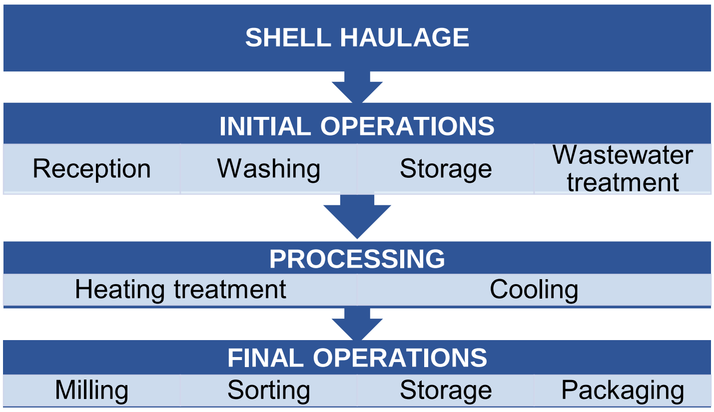
The cradle is located on the canning company, where shells are stripped from mussel. Consequently, transport to the recycling shell factory should be included. The gate is determined by the end of the production process, where the by-product is ready to be sold.

In this paper, the uses for MS are unbound construction applications, such as insulating material, material for correction of graded aggregate, or filler material in drainage channels. According to this, the functional unit is a generic metric ton of MS adapted for its use as an aggregate for construction purposes.

3.3 Life Cycle Stages

Lifecycle for obtaining granular material differs slightly from that required for obtaining calcium carbonate. The process consists of the stages indicated in Figure 1.

Figure 1. Production of gravel, sand and filler by MS valorization.



1. *Shell haulage*. This stage includes haulage from origin (canning companies) to the recycling factory. Considering the location of the main canneries and valorization factories that currently exist in Galicia, 100 km has been taken as an average calculation distance.
2. *Initial Operations*. These steps involve reception, storage and washing of shells. Shells are washed with fresh water to reduce the salt content of the final product, preventing equipment from corrosion. It is considered that the factory incorporates waste water treatment installations.
3. *Processing*. This stage includes drying, heat treatment and subsequent cooling of shells. For obtaining $CaCO_3$ (Iribarren, 2010), the material needs a calcination process, with temperatures of 190 ºC for 18 minutes and 550 °C for 15 minutes. However, according to information provided by suppliers and experts in this field, a simple heat treatment at a temperature of 135 °C for 32 min serves for removing the organic matter of the shells. Moreover, a gas treatment is not necessary (Iribarren, 2010). Compared to calcination, considering the aforementioned factors, and taking into account that the interrelation between treatment temperature and energy consumption (and emissions) is not linear, the potential emissions and energy consumption due to the heat treatment decrease by 75%. Finally, the required cooling process is also reduced. Temperature needs now to be lowered by 75 °C (from 135 ºC to 60 ºC), instead of 490 °C (from 550 ºC to 60 ºC). So it is not necessary to use water spray, but only an air stream (Iribarren, 2010). Thus, the potential impacts due to the cooling process decrease by 90%.
4. *Final Operations*. These involve milling, classification, storage, and packaging. Once cooled, the shell is milled to obtain different grain sizes. Milling consists of three phases: grinding (up to 8 mm; gravel), screening (up to 4 mm; sand) and micronizing (less than 0.063 mm; filler). Thus, an appropriate particle size according to market requirements is provided. In this paper the production of gravel, sand and filler is addressed. Gravel and sand only require grinding and screening. In contrast, filler production demands the three phases. The MS aggregate has a wear resistance and very high impact strength. It presents a Los Angeles coefficient close to 20%.

3.4 Results

Table 1 contains estimations for the main emissions and energy consumption indicators for obtaining gravel, sand, and filler from MS. Due to the previously alluded differences related to the heating and milling treatments, the impacts are much lower than the ones estimated by Iribarren (2010) for obtaining $CaCO_3$.

Table 1. Estimations of emissions and energy consumption for MS aggregate

Functional Unit: 1 metric ton of material	Units	Gravel and Sand	Filler
Abiotic depletion potential (ADP)	kg Sb eq.	8,38E-01	1,02E+00
Global warming potential (GWP)	kg CO_2 eq.	2,42E+02	3,33E+02
Ozone layer depletion potential (ODP)	kg CFC^{-11} eq.	1,38E-05	1,51E-05
Human toxicity potential (HTP)	kg 1,4-DB eq.	2,08E+01	2,49E+01
Fresh water ecotoxicity potential (FETP)	kg 1,4-DB eq.	9,57E+00	1,10E+01
Marine aquatic ecotoxicity potential (METP)	kg 1,4-DB eq.	1,72E+04	2,09E+04
Terrestrial ecotoxicity potential (TETP)	kg 1,4-DB eq.	3,04E+00	3,08E+00
Photochemical oxidant formation potential (POFP)	kg C_2H_4 eq.	5,50E-02	6,29E-02
Acidification potential (AP)	kg SO_2 eq.	1,10E+00	1,31E+00
Eutrophication potential (EP)	kg $PO_4{}^{3-}$ eq.	1,17E+00	1,18E+00
Energy (E)	MJ	5,17E+02	6,64E+02

3.5 Comparison of MS aggregate versus conventional one

The results obtained in the previous section allow comparing the aforementioned impacts with the ones referred to conventional aggregates, estimated by using the Ecoinvent (2015) Database (Table 2). Without taking into account other environmental indicators (for instance, the positive environmental impact associated with the use of waste, instead of sending it to landfills), the recycled solution has higher environmental impacts than the conventional one. In addition to the processes for removing organic debris, other reasons external to the production process make higher these emissions and the energy consumption. The low number of recycling centers in Galicia often involves long transportation distances. Furthermore, recycling factories have a low production volume, as the main destination of shells is still landfill (only 30,000 t per year of MS are processed compared to 80,000 t generated in Galicia). This situation would improve if most of the shell from canneries were employed after the corresponding recycling process. In that case, an increased activity would lead to higher profitability of recycling plants, and this could allow new investments for expanding those installations and modernizing the technologies employed.

4. Indicators for assessing construction systems incorporating MS

Despite of the previous comparative results, MS aggregate could have global sustainability advantages when compared to conventional aggregate, if additional environmental, social and economic indicators are considered. The authors are currently performing a wider analysis including other indicators that will be referred to here.

Achieving sustainability requires a holistic approach that balances economic (productive life) and environmental (life in harmony with nature) aspects, as well as social concerns (healthy life) (United Nations, 1992; Azapagic, 2003). Sustainability is being incorporated into products and services in many industries and businesses, and the construction industry is not an exception (Fernández-Sánchez & Rodríguez-López, 2010). However, real implementation by companies remains inadequate. Construction projects require application methods and tools for sustainability assessment (Tsai and Chang, 2012), considering wider sets of indicators for the three referred to pillars.

Table 2. Estimation of the main emissions and energy consumption for MS and conventional aggregates

Functional Unit: 1 metric ton of material		*Conventional Aggregate*	*Shell Aggregate*
Global warming potential (GWP)	kg CO_2 eq	6,30E+00	2,42E+02
Ozone layer depletion potential (ODP)	kg CFC11 eq	2,00E-07	1,38E-05
Acidification potential (AP)	kg SO_2 eq	3,80E-02	1,10E+00
Eutrophication potential (EP)	kg $PO4^{3-}$ eq	4,00E-03	1,17E+00
Photochemical oxidant formation potential (POFP)	kg C_2H_4 eq	6,00E-03	5,50E-02
Energy (E)	MJ	1,74E+02	5,17E+02

Sustainability indicators help decision makers to assess sustainable performance and reduce the amount of data (Hourneaux et al., 2014). They serve for translating sustainability issues into quantifiable measures of economic, environmental and social performance. Identification of relevant issues is critical in the development of indicators. Nevertheless, nowadays it can be very difficult or impossible to find real quantitative data related to specific social and even economic indicators. This leads to the consideration of qualitative ones, estimated by experts and normally expressed by means of semantic labels (high, medium, low).

In the following subsections, a set of indicators for assessing sustainability is proposed. This set is useful for construction systems that incorporate MS, regardless of their application. It is structured in three levels. The first one includes the indicators to be assessed. The criteria level organizes and structures the problem. There is an intermediate level (risk level) to facilitate the understanding and organization of the model. The indicators included should take into account not only the issues related to the MS by-product and its use in the construction sector, but also its influence on the canning industry, since its companies are provided with a tool for managing shell waste and saving money.

4.1 Environmental Dimension

Environmental indicators evaluate the status and evolution of certain environmental factors. They allow obtaining and analyzing information with the aim to assess impacts, take measures to prevent them, and monitor their compliance.

This must be done taking as reference environmental indicators commonly accepted by the international scientific community, related to energy and natural resources consumption, pollution of air, water and earth, emissions directly hazardous to human health, use of natural areas, and waste production, among others.

However, it is necessary to include additional features considering the case study. Construction products require large volumes of aggregate and their production directly involves habitat alteration. Furthermore, large areas for storing are required for these materials.

MS is removed to landfills if not recycled. It also involves land use, which is environmentally harmful due to discharges that may occur. Another peculiarity is the odor the shell can give off during manufacturing and even during a short first part of the product life time. In this regard, two factors must be considered: odor intensity and durability. Table 3 contains sustainable indicators for the environmental dimension.

Table 3. Environmental indicators

Criteria	Risks	Indicators
Resources consumption (C1)	Materials consumption	Materials consumption
	Energy consumption	Total energy
		Renewable energy
Discharges (C2)	Eutrophication	$PO4^{3-}$ Eq. emissions
	Acidification	SO_2 Eq. emissions
Emissions (C3)	Global warming	CO_2 Eq. emissions
	Summer smog	C_2H_4 Eq. emissions
	Ozone layer depletion	CFC11 Eq. emissions
	Acoustic pollution	Noise
	Odor	Odor
Ecosystems (C4)	Habitat alteration	Habitat alteration
Environmental management (C5)	Certification of supplying companies	ISO 9000, ISO 14000 and EMAS certifications
Land use (C6)	Land use	Areas affected by material extraction and accumulation
Waste (C7)	Waste generation	Generation of solid urban waste
	Waste consumption	Use of recycled materials

There are seven criteria. C1 refers to the use of resources, both materials and energy. C2 and C3 refer to discharges and emissions to the air, land and water, generated both in the manufacturing process and the production of raw materials. Ecosystems (C4) involve the reduction of biodiversity rate and disappearance of species due to habitat alteration. Environmental management (C5) is related to the behavior of company in environmental matters. Land use (C6) is based on the necessary area for collection. Finally, the waste criterion (C7) considers the balance between generation and consumption of waste.

4.2 Economic Dimension

In general, the economic pillar considers aspects related to the costs of the life-cycle activities and processes. In this case, maintenance and waste management costs are beyond the scope of the cradle-to-gate analysis under development by the authors. Shell valorization involves the conversion of a waste material in a product, saving costs associated to waste management. Table 4 includes the economic indicators under study.

Table 4. Economic Indicators

Criteria	Risk	Indicators
Cost (C8)	Direct cost	Price
Value distribution (C9)	Influence on input industry	Reduction in production costs of canneries

Firstly, direct costs (C8) for contractors are considered by means of the sale price of the by-product. As explained above, data has not been found about indirect costs associated with products that incorporate MS. Moreover, a criterion of value distribution (C9) is taken into account. In this way, the cost reduction in canneries, due to the difference between the cost of removing the shell to landfills and the potential income for selling that waste, is taken into account.

4.3 Social Dimension

The social pillar of sustainability considers a number of socio-cultural aspects related to society welfare. It is based on employment generation, equal opportunities and social equality, education and training, culture, defense of social rights, or local wealth, among other issues.

From a social point of view, the mussel-cannery industry is a long-established one in Galicia. It is a clear example of redistribution of income based on small and medium-sized family businesses with an employment generation of 11500 permanent jobs. Women also have a strong role in this industry. All these considerations certainly result in a social gearing contribution in the local context.

In addition, mussel waste accumulation in poorly equipped areas creates an undesirable visual effect with serious damages from an aesthetic and landscape perspective, together with unpleasant smell. It is important to remember that canneries are usually located in tourist areas. Therefore, the by-product alternative can benefit the public image of the cannery sector.

Frequently the social dimension is not adequately approached, due to the lack of analytical and theoretical foundations and, sometimes, to a lack of awareness (Vifell & Soneryd, 2012); and it is indispensable to give it the consideration that deserves. Nevertheless, the current crisis calls for a treatment that goes beyond what has been done so far. Moreover, social issues could establish considerable differences in this project.

Table 5 includes the proposed social indicators. First of all, employment and workers (C10) have been considered. The promotion of women's employment is also a relevant aspect, as the canning industry employs higher percentage of female workers than the construction sector. Employment quality should also be evaluated, taking into account salary levels and casualization of employment. An important indicator, counterproductive for the MS by-product, will be the absence of legislation and regulations for its use (C12). The use of local products (C14) is also taken into account. Finally, this proposal also considers the social indicators established by the Sustainability Appendix of the Spanish Structural Concrete Code (EHE-08; *Ministerio de la Presidencia*, 2008), grouped into the criteria of citizens (C11) and innovation (C14).

Table 5. Social Indicators

Criteria	Risks	Indicators
Employment and employees (C10)	Unemployment	Employment generation
		Promotion of women's employment
	Employment quality	Temporary work
		Salary level
	Workplace accidents	Voluntary health and safety measures
		Accidents at work
	Training	Employee training
Citizens (C11)	Information and interest	Public information website about the project
		Project declared of general interest by Public Administration
Legislation and regulations (C12)	Absence of specific legislation	Laws, regulations, standard codes related to the product
Innovation (C13)	Innovation	Application of innovative methods resulting from R&D projects.
Local wealth (C14)	Local wealth	Use of local materials

5. Conclusions and future work

Recycling activities are commonly shown to have lower environmental impact than the production of the corresponding goods from raw materials. This work presented an emissions and energy consumption LCA for MS valorization. Its results show that the MS aggregate production has higher impacts than those for producing conventional aggregate. However, the decisions should be made bearing in mind a global sustainability view. On the one hand, it is necessary to introduce additional environmental indicators, as depletion of natural resources, waste consumption and generation, habitats alteration, or land use.

On the other hand, the management of mussel waste has been assessed from a mere environmental perspective in other studies, whereas the potential economic and social aspects have not been analyzed. This will give a definitive answer to the question here posed both, from a general sustainability perspective, and from a pure environmental one.

This paper attempts to address this gap by identifying the key indicators related to MS valorization. On the basis of this work, future research can be approached in order to quantitatively assess the effectiveness and adequacy of the use of MS by-products in the construction sector. Methods for integrating different indicators' assessment can be used, such as the Analytic Hierarchy Process (AHP) or the MIVES method (Integrated Value Method for Evaluating Sustainability). It should be considered that there is always some degree of uncertainty about the real values of the proposed indicators. This could be dealt with using probabilistic simulation methods.

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