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Circular economy for sustainable building: environmental and economic impacts of a green mortar with foundry sand waste

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Abstract

The study of solid waste reuse and recycle for sustainable construction is attracting the attention of researchers and practitioners due to the low cost, the high availability and the potential properties of waste materials. This paper introduces a research aimed at analyzing the economic and environmental impacts of a sustainable construction material, i.e. an innovative green mortar. Such mortar was obtained from the reuse of the foundry sands of an Italian automotive company. The aim was to realize a sustainable product, proposing the reuse and the valorization of the wastage left over of a manufacturing process. In this paper, the characteristics of the green mortar as a cement aggregate replacement were investigated, together with the economic and the environmental impacts of such material. The methodologies adopted in this research include the Life Cycle Assessment of the green mortar and the cost-benefit analysis for the production process. The results confirm that the adoption of a circular economy-based management for the foundry sands would allow economic and environmental benefits for all the actors involved in the supply chain of the green mortar.

Keywords: circular economy; sustainability; green mortar; sustainable construction.

1. Introduction

The global use of primary natural resources is expected to increase by four times within 2050 (Menikpura et al., 2013). This exploitation of natural resources is causing the over-production of Solid Waste Materials (SWM). However, the increasing demand for new products is accelerating such trend. The global volume of natural resources used in construction industry and in transport infrastructures has increased by twenty-three times between 1900 and 2010 (Gurumoorthy & Arunachalam, 2019). Consequently, the demand for concrete has rapidly increased in the last years. Sand and gravel are the most extracted primary materials in the industrialized countries. The over-extraction of the sands and the lowering of the riverbeds are causing the reduction of the groundwater table and the costal erosion. In response to such phenomenons, local governments are imposing restrictions to sand extraction from the riverbeds, determining a significant increase of the price for primary construction materials (Bhardwaj & Kumar, 2017). In 2018, the global consumption of concrete was approximately 4 billion tons. The same year, the

Italian concrete production was roughly 19.3 million tons, 2% less than in 2014 (AITEC, 2018). In this context, the need for sustainable concrete is a global issue that is reaching the attention of the global construction industry (Martins et al., 2019).

The mortar is a building material composed of multiple products, as cement, fine sands and water. Mortar is not as strong as concrete. It is typically adopted to hold together masonry materials, e.g. bricks, concrete blocks and stones. The composition of the elements in the mortar defines its final structural properties (Pandey & Agarwal, 2019). The adoption of SWM for the production of sustainable building materials, e.g. the mortar, is one of the multiple challenges of the emerging sustainable construction industry (Hayles & Kooloos, 2008; Matos et al., 2019). Furthermore, the rising cost of sand for concrete is increasing the prices of buildings and constructions in the last decades. The reuse and the recovery of industrial SWM, e.g. the downstream products of the manufacturing processes, for the development of sustainable building materials offer a valid support for problems associated with the final disposal of industrial waste (Roy & Sairam, 2019). Previous studies and researches have investigated the reuse of different waste materials for the production of sustainable mortar with high physico-chemical properties, good resistance and high flexibility (Atiyeh & Aydin, 2020; Aydin & Arel, 2019; Chandra Paul et al., 2018; He et al., 2020; Hossain & Thomas Ng, 2019; Li et al., 2020; Massoudinejad et al., 2019; J. Wang & Wang, 2019; Z. Wang & Geng, 2015). In 2009, two Italian companies, leaders in the automotive industry and in the production of chemical products for construction, with the support of a research team from the University of Modena and Reggio Emilia, developed a green mortar, i.e. a sustainable building material obtained from the downstream foundry sands of the automotive manufacturing processes. Since then, multiple variants of such green mortar have been tested in laboratory, aiming to define the optimal composition of the chemical elements in the mortar. This paper introduces the results of the analysis of a new variant for the green mortar containing more than the 70% of foundry sand retrieved from the manufacturing processes of the automotive company involved in the study. The aim was to assess the economic and the environmental impacts of the product in the context of green construction and sustainable building (Václavík et al., 2020).

The remainder of this paper is structured as follows: Section 2 introduces a brief overview of the circular economy principles for sustainable development and for the production of green building materials; Section 3 defines the materials and the methods adopted in this study; Section 4 provides the results, discussing the economic and environmental impacts of the developed green mortar; finally, Section 5 describes the limitations of this study and the opportunities for future research.

2. Literature review

2.1. Circular economy and sustainable development

The diffusion of the culture of environmental sustainability has been spreading in both developed and developing country in response to the extreme climate phenomena that are affecting urbanized areas all over the world. The increasing global population and the rising lifestyle standard levels are leading the global economy to the excessive exploitation of the natural resources, causing an extreme impact on climate change, air pollution and global warming (Hoornweg et al., 2015; Menikpura et al., 2012, 2013). However, the economic growth is possible and environmentally sustainable when the use of natural resources is limited. The challenge of sustainable development is to satisfy the requirements of modern progress with no impact on the resources for the development of the future generations. The European Commission estimates that the global use of primary natural resources will quadruple by 2050 (EurActiv, 2011). In 2009, a research revealed that about 125 billion tons of natural resources are consumed globally every year. Such resources produce up to 4 billion tons of solid waste (Chalmin & Gaillochet, 2009). Recent statistics expect a 70% increase of the annual production of solid waste in 2050, due to increasing urbanization and population growth (Kaza et al., 2018). These data confirm the need to find alternative resources for sustainable development, which might be retrieved from the downstream products of the industrial processes.

Increasing resource efficiency and achieving higher environmental results are the major pillars of the European growth strategy for a smart, inclusive and sustainable economy, i.e. the European Green Deal (EGD). The EGD is the Europe's agenda for sustainable growth, which supports the transaction from a traditional linear economy based on resource consumption, to a sustainable model focused on resource efficiency and low-carbon economy (European Commission, 2019; Macarthur, 2020; The Ellen MacArthur Foundation, 2012). In this context, governments and social systems are promoting the adoption of sustainable policies for waste management in both private and public organizations (European Commission, 2014, 2019; European Parliament & European Council, 2008; Shekdar, 2009). The European Commission has adopted a new Circular Economy Action Plan (CEAP), which is one of the main blocks of the EGD (European Commission, 2020). The aim is to promote the adoption of a sustainable approach along the entire life cycle of products, from the design process through production, use and disposal. The target areas of the CEAP are the sectors that use most resources and where the potential for circularity is high, such as electronics and ICT, batteries and vehicles, construction and buildings. The measures and the actions required for implementing a circular system include the design of sustainable products, the empowerment of consumers and public buyers, reduced usage of natural resources and waste elimination. Circular systems promote material reuse, recovery and recycling to realize a closed-loop system and to reduce pollution and carbon emissions (Geissdoerfer et al., 2017; Reike et al., 2018). Figure 1 shows the circular economy model, based on the reuse and the recycle of the process outputs, and the comparison with the traditional linear economy model.

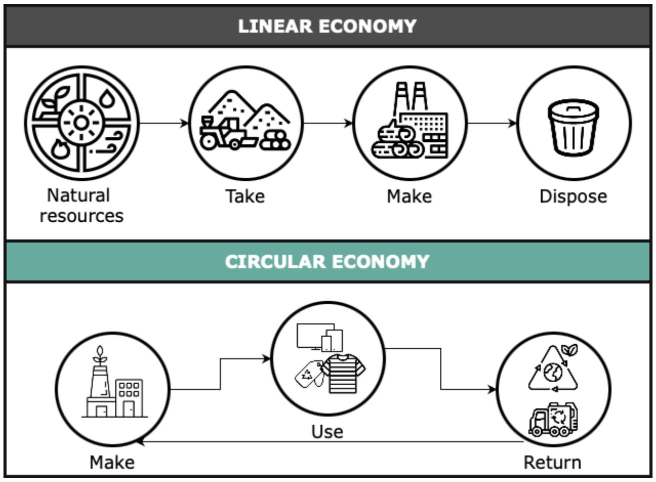

Figure 1. Linear economy (top) and circular economy (bottom) models.

The focus of linear economy business models is on the consumption of natural resources and the disposal of waste materials (Figure 1, top). A circular system builds economic, natural, and social value through the transition to renewable energy sources, surpassing the "take-make-dispose" extractive industrial model of linear economy-based systems (Macarthur, 2020). The circular economy model regenerates the natural systems by keeping materials and products in use and designing waste and pollution out of the system (Figure 1, bottom). Consequently, a circular economy-based system allows higher resource productivity because products, equipment and infrastructure are in use for longer (Invernizzi et al., 2020). Energy and waste products are inputs to other industrial processes, as components or recovered resources. In 2014, the European Zero Waste Program proposed a set of objectives for improving waste management and encouraging the development of new recycling and treatment technologies. European Member States were invited to promote research into environmentally friendly and cost-effective recycling methods, reducing waste disposal and providing incentives for rising public awareness about the environmental problem (European Commission, 2014). It was estimated that eco-friendly design and waste reuse together allow up to 600 billion euros saving for companies and organizations. Waste reuse could satisfy from 10% to 40% of the European demand for raw materials, leading to a 40% reduction of gas emissions by 2030 (European Commission, 2014).

2.2. Circular economy and sustainable building

The construction industry is a critical target area of the European CEAP, thanks to its high potential for circularity. This industry is responsible for high consumptions of energy, intensive gas emissions in the atmosphere and production of large quantities of SWM (Zimmermann et al., 2005). About half of the non-renewable resources consumed for human activities are used for infrastructure and building construction, which make this industry one of the least sustainable in the world. The resource shortage and the negative environmental impacts of construction activities are causing a growing interest of construction companies and research teams towards the production of second-generation building materials. The modern construction industry acknowledges the importance of waste reduce, reuse and recycle. In the last years, many researchers have investigated the structural characteristics of construction materials, as concrete and mortar, in which different SWM replace the fraction of conventional fine aggregates (Alqahtani et al., 2021; Amin et al., 2020; Faridmehr et al., 2020; Mohammadhosseini et al., 2019; Obaid et al., 2021; Restuccia, 2019; Thanon Dawood & Hani Abdullah, 2020). (Bassam A. Tayeh Doha M. Al Saffar, 2018) investigated the use of recycled iron powder as a sand replacement for the production of cement mortar. The authors concluded that the compressive strength performances of the mortar decrease with the increased amount of recycled iron powder in the mixture. However, increased flexural strength is associated with the increased percentages of recycled powder in the mortar. (Nahi et al., 2020) studied the characterization of the properties of mortars and cement pastes made with powdered soda lime waste glass. The results of their study show that the amount of cement replacement by glass powder plays a critical role in determining the mortar characteristics. Specifically, high glass powder replacement of cement paste increases the hydration reaction rate. Compressive strength and dynamic Young's and shear moduli values decrease with increasing glass powder content. Recently, (Aadi et al., 2021) investigated the use of aluminum waste chips as a sand replacement in cement mortar. The authors concluded that cement mortar with low percentages of aluminum waste (5%) is suitable for structural applications. Higher percentages of aluminum waste allow the production of lightweight cement mortar for non-structural applications. The study from (Thorneycroft et al., 2018) proposed the partial replacement of fine sand in cement mortar with plastic waste materials. The results reveal that a 10% of sand replacement would potentially allow a saving of 820 million tons of sand per year. (Kanadasan et al., 2018) developed a palm oil clinker from the combustion of the palm shells and fibers. The obtained material revealed good technical, environmental and economic performances. Other studies focused on the analysis of biochar as a further additive replacement for cement mortar. Biochar is a carbon-rich material which can be obtained from different organic waste products, such as sewage sludge and agricultural waste (Gupta et al., 2018; J. Wang & Wang, 2019). (Gupta et al., 2018) analyzed the use of the biochar obtained from food and vegetable wastes, such as rice and mixed saw dusts, in the cement mortars. The results revealed the potential of the biochar as an additive component of cement mortar for civil engineering assets.

In the last decades, various studies proposed the reuse of construction and demolition waste as recycled aggregates for the production of sustainable cement mortar and concrete (Adamson et al., 2015; Akhtar & Sarmah, 2018; Behera et al., 2014; Çakir, 2014; Felekoğlu et al., 2007; Shi et al., 2016; Zhan et al., 2016). Recycled aggregates offer the advantages of reducing or avoiding the extraction of new natural aggregates, the disposal in landfills and the environmental pollution (Napolano et al., 2016; Serres et al., 2016; Tam et al., 2018). However, the percentage of recycled aggregates should be between the 30% and the 50% of the natural aggregates in the mixture (Akhtar & Sarmah, 2018). (Makul & Sua-Iam, 2018) investigated the use of recycled foundry sands as a replacement for the Portland cement used in the mixing of concrete. The results were promising in terms of compressive and bending strength of the recycled mixture. The authors concluded that the recycled sands should not exceed the 30% of the mixture weight to preserve the structural performance of the material. In this research, the use of the foundry sands produced in the automotive industry was investigated for the production of an innovative green mortar. The foundry sands adopted in this study are the outputs of the melting processes in the automotive industry, for the manufacturing of the motor components (Siddique & Singh, 2011). The aim was to analyze the economic and the environmental impacts of the proposed product and the potential for circularity of the production process.

3. Materials and Methods

The green mortar investigated in this study was developed in the laboratory of an Italian company leader in the production of chemical products for the construction industry. The foundry sands adopted for the production of the green mortar were from the casting mold wastes of an Italian luxury sports car manufacturer. Different variants for the mortar were tested in laboratory prior to the present research, aiming to define the optimal composition of the mixture that ensure good bending and compressive strength. The composition of the green mortar adopted in this study is in Table 1.

Table 1. Composition of the green mortar adopted in this study.

Component	Percentage
Cement	12.00%
Additives	0.06%
Fine sands	17.50%
Foundry sands	70.43%
Total	100%

The foundry sands retrieved from the automotive manufacturing process make up more than two thirds of the final composition of the green mortar (Table 1).

3.1. LCA analysis

The environmental impacts associated with the proposed product was assessed using the Life Cycle Assessment (LCA) methodology. LCA is increasingly adopted for supporting decision-making in the design of buildings and infrastructures (Hollberg et al., 2020, 2021; Obrecht et al., 2020; Safari & AzariJafari, 2021). Four phases characterize this methodology: goal and scope definition, inventory analysis, impact assessment and interpretation (Koffler et al., 2020; The International Standards Organisation, 2006). In this study, the LCA was adopted to understand the economic and the environmental profiles of the green mortar, comparing them to those of the traditional product. Figure 2 shows the processes investigated in this study, i.e. the green mortar and the traditional mortar production processes.

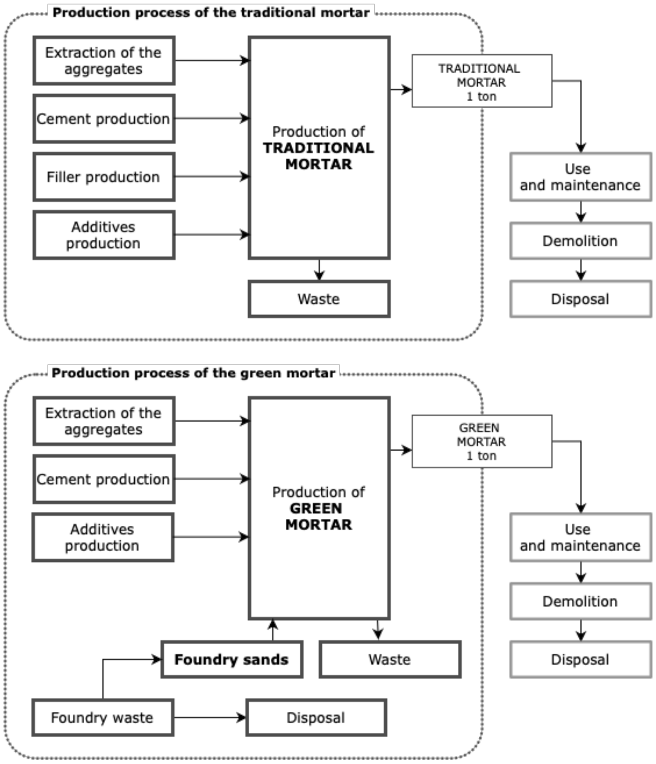

Figure 2. Production process of the traditional mortar (top framework) and production process of the green mortar (bottom framework).

The dotted lines in Figure 2 define the system boundaries for the LCA, as required by the International Standard ISO 14044 (The International Standards Organisation, 2006). Specifically, the production process of the green mortar does not include the processes required for the production of the foundry sands arriving at the automotive company. The product ton is the reference functional unit. The inventory analysis includes the data collection with the SimaPro 7.3.3 software. Primary data, i.e. data available on-site, were from interviews, investigations and technical inspections performed in the production sites. The car manufacturer provided the data related to the foundry sands and to the motor manufacturing processes. The producer of chemical products for construction provided the data related to the traditional and the green mortars production processes, e.g. the cost of materials and equipment, and the energy consumption for material extraction, processing, road transport and material handling. Table 2 shows the sub-processes and the functional units considered in the environmental impact analysis.

Table 2. Sub-processes and functional units in the environmental impact analysis for the traditional mortar production process and for the green mortar production process.

Traditional mortar	Green mortar
Sand extraction [1 ton of extracted sand]	Mortar production [1 ton of mortar]
Sand washing [1 ton of washed sand]	
Sand processing [1 ton of processed sand]	

The production process of the traditional mortar consists of three sub-processes, i.e. sand extraction, sand washing and sand processing (Table 2). The functional units adopted for the environmental impact analysis were 1 ton of each sub-product. The production process of the green mortar has no sub-processes, i.e. 1 ton of green mortar was the functional unit for the environmental impact analysis.

Secondary data, e.g. the data related to the inert material processing, were obtained from the Ecoinvent database (Ecoinvent, 2021) and from the Environmental Product Declaration (Ibáñez-Forés et al., 2016). The impact assessment aimed at understanding and quantifying the environmental impact of the production processes. The ReCiPe Midpoint methodology was adopted for the impact assessment (Goedkoop et al., 2008). This methodology provided the environmental profile of the investigated products, i.e. the traditional mortar and the green mortar, as the impact on the climate change, the water exploitation and the soil use. The opensource OpenLCA software was adopted for the environmental impact analysis (OpenLCA). The software supported the design of the supply chain model for both the traditional and the green mortar production processes.

3.2. Cost-benefit analysis

The Cost-Benefit Analysis (CBA) in this study aimed at quantifying the economic and social impacts of a project, showing its cost-effectiveness in terms of obtained benefits and necessary costs. The benefits considered in the CBA are not limited to monetary incomes. In this study, the resource savings due to the mortar production processes were considered as benefits for the CBA. Resource consumptions were considered as system costs (ASFIM, 2018; Rosasco & Perini, 2018). The results of the CBA in this study supported the investigation of the cost-effectiveness of the green mortar production process and the analysis of the potential economic advantages over the traditional process.

4. Results and Discussion

This section introduces and interpretates the results of the LCA and the CBA for the reference mortar production processes. Table 3 shows the results of the impact assessment with the ReCiPe methodology.

Table 3. Results of the impact assessment for the traditional mortar and the green mortar. The functional unit is the ton of produced mortar.

Impact category	Traditional mortar	Green mortar	Differential
Agricultural land occupation [m^2*a]	102.84	102.14	-1%
Climate Change [kg CO_2 eq]	175.96	153.55	-13%
Fossil depletion [kg oil eq]	38.71	29.62	-23%
Freshwater ecotoxicity [kg 1.4-DB eq]	0.96	0.59	-39%
Freshwater eutrophication [kg P eq]	0.02	0.02	-19%
Human toxicity [kg 1.4-DB eq]	23.20	18.77	-19%
Ionising radiation [kg U235 eq]	12.33	11.51	-7%
Marine ecotoxicity [kg 1.4-DB eq]	0.88	0.54	-38%
Marine eutrophication [kg N eq]	1.02	0.90	-12%
Metal depletion [kg Fe eq]	4.38	3.58	-18%
Natural land transformation [m^2]	0.02	0.02	-5%
Ozone depletion [kg CFC-11 eq]	1.37 E-05	9.82E-06	-28%
Particulate matter formation [kg PM10 eq]	0.21	0.16	-25%
Photochemical oxidant formation [kg NMVOC]	0.44	0.37	-16%
Terrestrial acidification [kg SO_2 eq]	0.52	0.41	-20%
Terrestrial ecotoxicity [kg 1.4-DB eq]	0.02	0.01	-11%
Urban land occupation [m^2*a]	1.67	1.81	8%
Water depletion [m^3]	452.86	369.46	-19%

The results in Table 4 confirm the positive impact of the green mortar for 17 out of 18 impact categories in the ReCiPe methodology. The greatest advantages due to the use of recycled products for mortar production is on freshwater ecotoxicity (-39%) and on marine ecotoxicity (-38%). Minor advantages are on natural land transformation (-5%) and on agricultural land occupation (-1%). The environmental advantage due to the use of the traditional mortar is limited to its impact on the urban land occupation (8%). The lack of filler product in the green mortar impacts on these results, i.e. the total amount of aggregates in both the mortars is 87.9% but the percentage of sand in the green mortar is higher than in traditional mortar.

The results of the LCA revealed that the highest negative environmental impacts are for the processes required for the cement production and the energy consumption due to the mortar production. The cement production revealed the negative impact of the mortar production processes for 7 out of 18 impact categories (9 for green mortar production), i.e. cement production requires material- and energy-intensive processes. Sand washing causes a negative environmental impact on 15 impact categories because of the use of electricity in both the traditional and the green mortar production processes. In general, the comparison between the two mortar production processes reveals strong analogies in terms of impact categories determining a negative environmental impact, i.e. both the investigated mortar production processes adopt electricity, methane, plastics and pallets. The seriousness of the impact depends on the presence of different aggregates in the production processes. The lack of filler, the use of oil and the foundry sand transport in the green mortar production process cause additional differences between the two processes. However, the adoption of recycled aggregates in the green mortar allows greater environmental benefits.

Table 4 shows the cost distributions obtained from the CBA for the traditional mortar and the green mortar production processes.

Table 4. Cost distribution for the traditional mortar and the green mortar production processes.

	Traditional mortar [€/t]	Green mortar [€/t]
Total cost of the sand	7.42	11.51
Cement and additives	13.00	13.00
Packaging products (pallets and bagging coils)	15.00	15.00
Packaging resources (human resources, plant and material handling)	15.00	15.00
Total	50.42	54.51

These results show the economic advantage of the traditional mortar over the green mortar. The total cost of the sand used for the production of the traditional mortar includes the cost of materials, machinery and energy deployed for sand extraction, washing and processing. Similarly, the cost of the foundry sand for the green mortar includes the costs for sand transport and disposal. Specifically, the total cost of the sand in the traditional mortar (7.42 €/t) includes the cost of washed sand (5.22 €/t) and the cost of processed sand (2.20 €/t). The total cost of the sand in the green mortar includes the cost of fine sand (4.11 €/t) and the cost for sand transport from the automotive company (7.40 €/t). The use of the foundry sand waste produced in the automotive company would allow the production of about 1500 t/year of green mortar and a total cost of nearly 81000 €. In 2016, the construction material producer involved in this study produced 23600 tons of traditional mortar, with a total cost of nearly 1.2 M€. The partial replacement of the sand in the mortar with the foundry waste from the automotive company would cost nearly 6000 € (see in Table 5).

Table 5. Cost distribution for the sands used in the traditional mortar and in the green mortar production processes. The costs refer to the production of 1500 tons of mortar.

	Traditional mortar [€/t]	Green mortar [€/t]
Fine sand		6060
Foundry sand transport		10900
Washed sand	7690	
Processed sand	3240	
Total cost	10930	16960

The cost for the transport of the foundry sands from the automotive company to the construction material producer produces high impact on the total cost for the sands in the green mortar (Table 5). This cost is borne by the construction material producer. The automotive company benefits from the economic advantage due to the elimination of the costs for the foundry waste transport and disposal. In conclusion, the CBA for the green mortar supply chain confirms the overall positive balance and the economic benefits for the automotive company over the costs borne by the mortar producer.

5. Conclusions

In the last decades, the over-exploitation of natural resources required to reach the goals of economic progress has produced negative effects on the environment, causing the reduction of these resources and the increase in the costs of construction materials. The necessity to reduce the use of natural resources and the increasing attention of socio-economic systems on sustainable development are driving the transition of an increasing number of construction industries toward sustainable business models (Fořt & Černý, 2020). The traditional "production-consume-disposal" business model does not meet the requirements of sustainability. Sustainable organizations are transitioning to circular economy, adopting the "reduce-reuse-recycle" circular business model to produce sustainable innovation.

In this context, the present research aimed to extend the life cycle of the downstream products of a manufacturing process, in a circular economy perspective. The foundry sands from an automotive company were adopted in the production process of a high-quality green mortar for construction.

The first goal was to verify the economic and the environmental benefits of the circular production model for the production of the green mortar over the traditional production process. The results from the LCA analysis for the green mortar production process proved the beneficial impact on the environment. The positive impact is due to the adoption of recycled aggregates for the production of the green mortar. The environmental advantage due to the use of the traditional mortar for construction is limited to its impact on the urban land occupation.

The second goal was to assess the economic impact of the mortar production processes. The results of the CBA revealed the higher cost of the green mortar compared with the cost for the production of the traditional mortar. The cost difference is due to cost of the inert material adopted for the production of the green mortar. Specifically, the transport of the foundry sands from the automotive company to the construction material producer produces high impact on the final cost of the green mortar. This cost would be borne by the construction material producer. However, the automotive company benefits from the economic advantage due to the elimination of the costs for the foundry waste transport and disposal. Finally, the CBA confirms the overall positive balance on the green mortar supply chain. Future developments of this study will investigate the use of different fine sands for the production of the green mortar and the environmental impact of the production process.

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