SUSTAINABILITY EVALUATION OF NATURAL AND RECYCLED AGGREGATES THROUGH LIFE CYCLE ASSESSMENT

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Summary

As basic materials for the construction industry, building aggregates play an important role in the debate relevant to the sustainability of buildings. The massive energy and natural resources use, that has characterized the construction industry ever since, explains the general interest in turning buildings less energetic expensive and more environmentally friendly. However, while focus has been limited for a long time to the operational period of the building, only during the last years Life Cycle Assessment (LCA) has been used as a tool for quantifying natural resources consumption and pollutant emissions with reference to the whole life cycle of building assets. With this approach, some important factors that were neglected for decades, such as the embodied energy and environmental interventions relevant to construction materials, started to be considered. As building aggregates must be produced according to socio-economic and environmental sustainability principles, the paper will analyze the main economic and energetic-environmental constraints characterizing natural aggregates production, by paying attention to the contribution of the different beneficiation steps and making use of the LCA methodology. Moreover, the paper will deal with alternative low grade sources of building materials, namely secondary materials from building demolition and rubble recycling, which could partially replace natural aggregates.

1. Technical, economic and environmental issues relevant to building aggregates

The importance of building aggregates for the construction industry – sand, gravel, crushed stones and tout-venant – is often underestimated. They should, in fact, be considered amongst the most important mineral commodities, both in terms of produced quantities and market value. According to the statistics (Wellmer F.W., 2002) building aggregates steadly rank in the first position in terms of production quantity: roughly 18 billion tons in the year 2000, that accounts for 58% of the world total mining production. Moreover, building aggregates hold the fourth position in the world rank in terms of market value: 92 billion euro, which is lower than the market value of energy mineral commodities (oil, natural gas and coal), but higher than gold (24 billion euro) and ornamental stones (23 billion euro). Based on the analysis of these parameters, it becomes therefore clear that building aggregates hold an important role in the overall economy at both local and global scale. However, their most salient economic significance stems from their essential contribution to the construction industry. It is in fact the final use of mineral commodities the ultimate reason that stands at the very beginning of the mining production. Thus, because of their role of input raw materials, they represent the first step of the construction industry streamline, whose products are aimed at satisfying some of the most important needs of mankind. For these reasons, the availability of building aggregates must be considered strategic for the overall economic system. Even though it is a common understanding to consider building aggregates as "third class" raw materials whose supply and availability can always and easily be met, it must be recognized that, according to the different fields of employment, well defined technical performances are required.

In order to meet the specific technical requirements which characterize the different construction sectors, appropriate beneficiation processes aimed at enhancing technical characteristics of building aggregates are often required. As it usually occurs, natural raw materials undergo a primary abatement process by means of drilling and blasting or mechanical excavation, followed by one or more size reduction stages and finally wet or dry separation in order to remove unwanted materials. As the beneficiation process is carried on, the technical performances of building aggregates improve, but, on the other hand, production costs and energetic-environmental burdens increase, as well. Therefore, because of the environmental impacts that are always induced by virtually any industrial activity, it becomes of the utmost importance to find a reasonable balance between exploitation of natural resources and their proper management, in order to meet sustainable environmental protection requirements. However, the point is not whether exploiting or not exploiting mineral resources, but it is more a question of evaluating what should be the correct quantity of mineral commodities to be produced and what is the most suitable production process. Undoubtedly, building aggregates are essential and valuable resources for the economic and social development of mankind, but they must be produced according to economic and environmental sustainability principles.

1.1 Eco-profiles of building aggregates

Quarrying activities for the production of building materials, which can be considered the first step of the construction industry streamline, are often claimed to be responsible of a number of harmful environmental impacts. The common negative perception which is often associated to mining/quarrying by the general public, presently more and more concerned about environmental issues, can be interpreted in terms of a generalized increase of "environmental quality demand". However, in a densely populated country like Italy, for instance, rich in natural beauties, as well as industrialized, not surprisingly the environmental protection requirements often conflict against the market demand for raw materials.

Among the most strongly opposed environmental interventions connected to the extractive industry, it is possible to quote local scale effects such as visual impact and land quality degradation, but the analysis should also be extended to wider scale issues by encompassing, for instance, depletion of non renewable resources, with and without energy content, for the production of consumer goods that necessarily begins in a mining/quarrying site. From the local to the global scale, the extractive industry can therefore be associated to the environmental effects summarized in Table 1. The analysis of the relationship between the extractive industry and such environmental effects contributes to outline the environmental-energetic profiles of building aggregates. Although all the environmental effects quoted in Table 1 deserve interest and should therefore be avoided or relieved, it must be recognized that their relative importance is mostly a matter of subjective evaluation. Moreover, when dealing with extractive activities, even though the general opinion and several public administrations consider local scale burdens the most important, it must be noticed that such environmental effects are the most difficult to quantify, while for the regional and global scale it is possible to make use of well known and objective assessment tools (Badino et al.1998). In this paper, while for the local scale environmental effects the analysis is limited to the list quoted in Table 1, as far as the regional and global scale are concerned, the results of some investigations run by the Politecnico di Torino research staff (Badino et al. 2005) are here presented and discussed. Beyond the fact that environmental impacts ascribable to the extractive industry are numerous and difficult to quantify, they are also deeply inter-connected and influence each other. Therefore, when facing such issues one at a time, by means of a separate approach, without taking into account the scale of influence, the analysis can lead to contradictory results. Not surprisingly, the solution of a single environmental problem may cause further environmental consequences, sometimes worse than the previous one, or the problem is simply transferred elsewhere.

Table 1 . Environmental effects ascribable to the extractive industry and their scale of influence.

Environmental effects	SCALE OF INFLUENCE
Resources depletion	Global
Global warming	Global
Ozone depletion	Global
Acidification	Regional
Eutrophication	Regional/local
Photochemical smog	Regional
Human toxicity	Regional/local
Eco-toxicity	Regional/local
Waste generation	Regional/local
Visual impact	Local
Surface water pollution	Local
Land use	Local
Water resources use	Local
Dust emissions	Local
Noise / vibrations	Local
Traffic	Local

Because of the different environmental interventions that can be associated to the mining-construction production streamline, and because of the existence of direct and indirect issues to be taken into account, LCA methodology, standardized according to ISO14040 (ISO 1997), is being more and more used as a tool for quantifying natural resources consumption and pollutant emissions with reference to the whole life cycle of mineral raw materials. This is a methodological approach similar to the one adopted in the previous paragraphs in order to emphasize the economic significance of building aggregates. In fact, as for the market value that should be extended to the added value of the construction industry, the energetic and environmental performances of building aggregates should be assessed by encompassing their production, use and end-of-life.

With this in mind, in order to assist LCA practitioners when developing their LCA models, it is of the utmost importance to make available the energetic-environmental profiles of building materials, describing and analysing their production processes, from quarry to delivery: the so called eco-profiles. Eco-profiles represent therefore the starting point and the first part of a full LCA. They summarize, in fact, the energetic-environmental background of building materials, from their very beginning, in the earth's crust, until the time in which they enter the building worksite.

2. Natural aggregates

The European industry for the production of building aggregates accounted, in the year 2004, for around 25000 quarries which correspond to an estimated annual supply of 2.8 billion tons: 7 t per capita (source UEPG, 2005). As far as Italy is concerned, the Italian central statistics agency ISTAT estimates the national production of building aggregates around 288 million tons in the year 2004. The Italian production of building aggregates steadily increased at a annual growth rate of 1.7% during the last two decades, the country total supply being 193 million tons in the year 1980. Therefore, according to the official statistics, per capita production of building aggregates is about 5 t in 2004. However, ISTAT statistics sensibly differs in comparison with other sources, as well as Italian per capita supply differs from other industrialised countries. According to a research recently carried out by DITAG of Politecnico di Torino (Badino et al. 2006) the Italian average annual requirement of building aggregates in the period 2000-2010 can be estimated in 6.5 t per capita. In any case, for comparison, it is worth noticing that according to UEPG (European Aggregates Association) per capita yearly production of building aggregates is 6.5 t in Europe in 2004, the maximum per capita supply being 20 t in Ireland and the minimum being 1.4 t in the Netherlands. For comparison, per capita production of building aggregates in the USA was 8.7 t at the end of the 1990's (source USGS).

2.1 Case study 1: Ceretto quarry

In the following case study, which is framed within a wider life cycle assessment investigation relevant to concrete run by DITAG of Politecnico di Torino in the year 2004 (Martaspina, 2004), the main parameters relevant to the eco-profiles of natural aggregates, excavated from an alluvial deposit, will be summarised. The LCA model that has been developed in order to outline the eco-profile of natural aggregates, has considered all the physical exchanges, including use of natural resources, air, water and soil emissions, a well as generated waste from-cradle-to-delivery of the final product to the building worksite. The production worksite under analysis is a quarry where building aggregates are excavated from an alluvial deposit, under the water table, by means of a grab dredge (Ridinger) equipment. Ceretto quarry is located in the southern surroundings of Torino, along the left side of the Po river. The production of gravel and sand was around 500000 t in the year 2003.

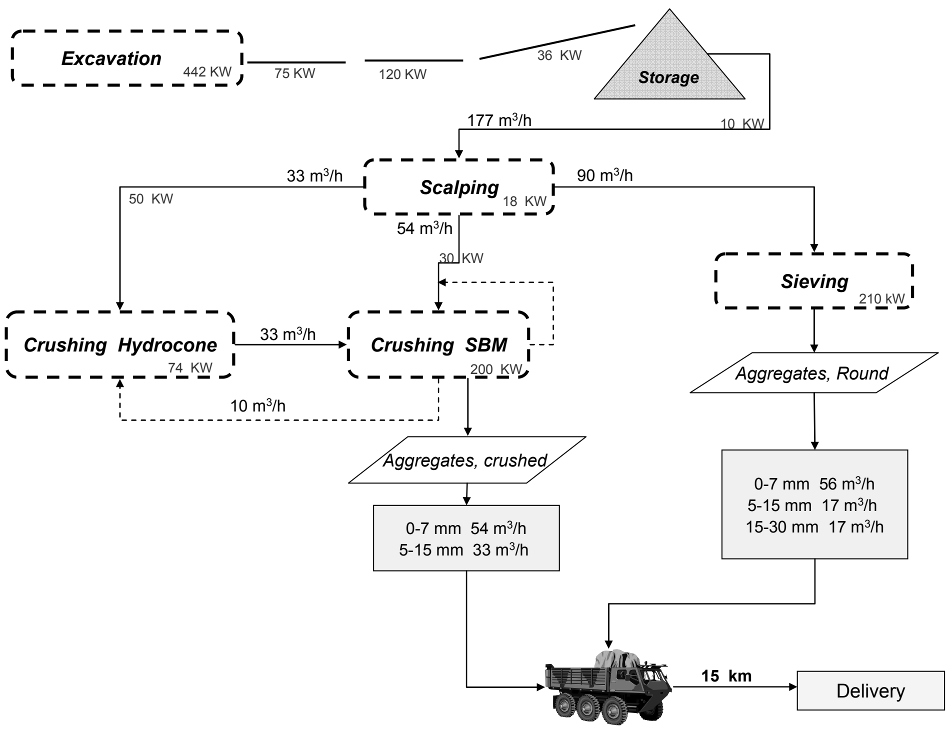

Figure 1. Main processes for the production of natural aggregates at Ceretto quarry.

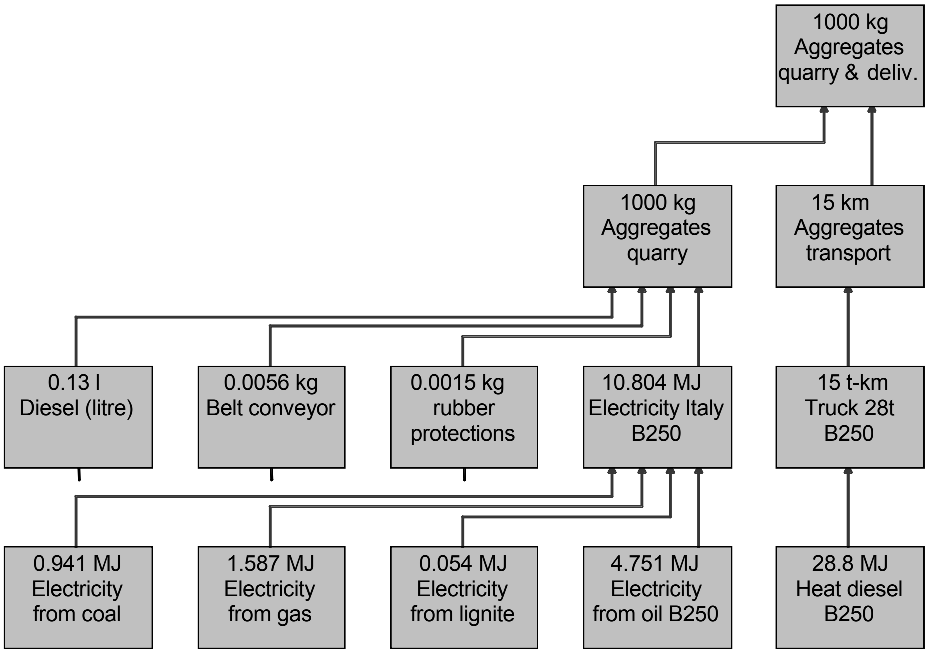

Figure 2. Flow chart relevant to production and transportation of building aggregates at Ceretto quarry.

The scheme in Figure 1 supplies an overview of the main industrial processes which characterise Ceretto quarry unit, with emphasis on main excavation, transportation and mineral treatment equipment, as well as some technical data. The software applications SimaPro6 and Boustead5 have been used, as supporting tools, in order to set up the LCA model, allowing inventorying of energetic and environmental intervention relevant to the production under study. Beyond the processes aimed at quarrying, crushing, sieving and piling the final products, for which energy consumption, as well as materials use, emissions and waste have been accounted, also the transportation to the final user, by means of a truck, for a distance of 15 km, has been included in the model.

According to the flow chart shown in Figure 2, the eco-profile model is built up by exploding the production process, starting from the outlet gate, going backwards along the production streamline. Each box represents a unit process or, in other words, an elemental industrial operation, which is connected up and downwards to other units. For each box, systematic information is collected, relevant to physical input and output from and to upstream and downstream operations. For each elemental industrial operation within the eco-profile model, a comprehensive physical ecobalance must be made available (Badino et al. 1998). Each box in Figure 2 calls up physical input/output from upstream operations, so that the top box carries on the cumulative environmental-energetic interventions of the whole production of building aggregates. Results gathered after the interpretation of the above described model, are presented in the next paragraph, jointly with the eco-profiles of sand and gravel that are available in different databases.

2.2 Eco-profiles of natural aggregates

From-cradle-to-gate LCA models, carried out in compliance with ISO 14040 recommendations, relevant to several building materials, including building aggregates, can be found in different databases. Table 2 summarizes some of the typical environmental impact indicators (eco-indicators), as gathered after the Impact Assessment step (ISO 1997), which can be regarded as representative of natural building aggregates eco-profiles. The first seven columns are relevant to sand and gravel LCA models included in different databases, while the last column refers to the building aggregates produced at Ceretto quarry. Energetic and environmental indicators given in Table 2 are typical of a LCA analysis (Badino et al. 1998). As far as energy use is concerned, in the case of GER (Gross Energy Requirement) indicator, the term “gross” indicates the cradle-to-gate energy and includes energy consumption from all ancillary operations, tracking all operations back to the extraction of raw materials from the earth crust. GWP (Global Warming Potential) as parameter relevant to greenhouse effect, AP (Acidification Potential) as parameter relevant to acid rain phenomenon, EP (Eutrophication Potential) as parameter relevant to surface water Eutrophication, POCP (Photochemical Ozone Creation Potential) as indicator of photosmog creation and, finally, waste generation are calculated by means of a cradle-to-gate approach. An analysis limited to the first two rows of Table 2 shows that the total energy requirement for the production, delivery and average transportation of 1 t of building aggregates ranges from a minimum of 58 MJ to a maximum of 163 MJ. Similarly, the production of greenhouse gases ranges from a minimum of 2.3 kg CO_2 to a maximum of 10.4 kg.

Table 2 . Main potential impact indicators representative of natural building aggregates eco-profiles, according to different sources.

From-cradle-to-gate Potential Environmental Impacts (data per 1 ton)	Unit	Gravel	Sand	Gravel & sand	Gravel, crushed	Gravel & sand, round	Gravel & sand, crushed	Gravel & sand, round	Gravel & sand, round
		ETH-ESU	ETH-ESU	IDEMAT	Ecoinvent	Ecoinvent	Boustead	Boustead	DITAG
Energy resources, GER	MJ	162.6	152.0	114.2	135.0	57.8	107.1	75.7	67.7
Global warming, GWP CO_2 eq	kg	10.4	10.0	8.7	4.2	2.3	6.7	5.7	4.6
Acidification, mol H+ eq	mol	1.69	1.59	2.97	0.88	0.57	2.18	2.43	1.70
Eutrophication, O_2 eq	kg	0.28	0.28	0.62	0.19	0.13	0.43	0.61	0.32
Photochemical smog, C_2H_4eq	g	0.54	0.53	0.16	0.35	0.12	0.13	0.08	0.06
Waste generation	kg	x	x	0.48	x	x	x	x	0.03

3. Recycled aggregates

Among “new” building materials that could replace the traditional ones, secondary materials from demolition and rubble recycling deserve more than some interest. The challenge is to deeply understand what destiny deserve construction and demolition (C&D) waste, whose quantities are becoming higher and higher, and to understand whether, and until what extent, such demolition materials can replace virgin building materials. In fact, from a certain point of view, the future aggregate quarries could be the old buildings to be demolished, but this must not be generalized. In fact, it is not fair to think that such new secondary “quarries” might completely displace the traditional ones. Quality requirements for commodities used in many industrial processes do not allow recycled materials use and, moreover, there are objective and insurmountable limits to recycling, which can be ascribed to decay of quality, loss of mass and energy as well as pollution caused during recycling processes. The solution probably stands in a fair equilibrium between traditional and secondary mines/quarries. It would be unwise to underestimate the ones or the others. In any case, this is a topic of great interest within the political debate about natural resources conservation on which, too often, some misconceptions are quite common. The point to be faced is the correct evaluation of what can be the effective contribution, in qualitative and quantitative terms, that recycled aggregates can supply in order to satisfy the requirement for building aggregates.

A careful evaluation, based on economic and environmental criteria, must be done relevant to the industrial process of recycling construction and demolition waste, in order to compare the two ways of producing building aggregates from virgin or recycled materials. In fact, only when it will be proved that the recycling process is both economically and environmentally sustainable, in comparison with the production of natural aggregates, the contribution of recycled aggregates could be considered positive. During the last years, excavation, construction and demolition waste (C&DW) management activities have faced a remarkable growth. In fact, their contribution, in terms of secondary raw material supply, as well as in terms of employment, presently represents a meaningful input resource to the manufacturing industry. According to the UE official data (Symonds et al. 1999), in the EU-15 the C&DW production was about 180 million tons at the end of the 1990’s, corresponding to about 500 kg per capita. An interesting remark is that relevant to the flows of C&D waste, which grew by 50% in Italy in the period 1999-2005 (APAT, 2005) and are nowadays comparable with the quantity of municipal solid waste.

The future perspectives of recycled aggregates strictly rely on the quality level requested for the different final uses. For example, organic and lightweight materials have to be absent in those recycled aggregates produced for concrete manufacturing and this condition implies remarkable technologic costs for the product valorisation, through dry or wet separation. On the contrary, for road construction, the lower required quality level may allow the presence of limited quantities of lightweight materials.

As far as Italy is concerned, official data says that the production of C&D waste has doubled during the last five years. In fact, per capita yearly C&D waste arose from 380 kg in 1998, to 740 kg in 2003. The Italian Association of Recycled Aggregates Producers (ANPAR) has estimated a total production of C&D waste around 40 million tons all over Italy in the year 2004. Based on C&D waste data relevant to Italy and considering the yearly requirement of building aggregates, according to the different sources, it is possible to make the following remarks. As far as the Italian per capita requirement of building aggregates is comprised between 6 and 11 t (Badino et al., 2006), the production of recycled aggregates represents a maximum potential contribution of about 10%, even in the theoretical case of a C&D waste recovery rate nearly 100%. For this reason, it is possible to state that recycled aggregates market cannot be considered as a potential substitute of natural aggregates.

The two typologies of aggregates must therefore not be considered as competitors but, on the contrary, their jointly use must be considered strategic. In fact, the construction industry could easily absorb the whole production of recycled building aggregates and use them as a mix of recycled and natural commodities in compliance with the different specific requirement of the final uses.

3.1 Case study: the CAVIT stationary rubble processing plant

The CAVIT plant is targeted to the C&D waste recycling, with a yearly average production of 150000 t, and performs a dry treatment on raw building rubble. The presently operating dry process is shown in Figure 4 and is characterized by:

- a feeding and scalping unit (1);
- a single stage crushing unit (2), setting up through an impact crusher and an overband separator, that removes the steel and reinforced re-bars;
- a silty rubble treatment unit (3), setting up through an overband separator and a screen, that separates the granulometric class <10 mm from the 10-40 mm class carrying on the process;
- a building rubble screening unit (4), where the 0-8 mm, 8-40 mm and 40-100 mm classes are divided;
- an air separation unit (5), that beneficiates only the 8-40 mm and 40-100 mm classes through the organic lightweight materials removal;
- a handling unit for piling up the final products (6).

At the end of the recycling process, aggregates are delivered within a distance of about 15 km by means of trucks. Figure 5, which refers to the LCA model relevant to the production of 0/40 mm class recycled aggregates at Cavit plant, can be useful in order to understand how the LCA methodology has been applied to the processes shown in Figure 4.

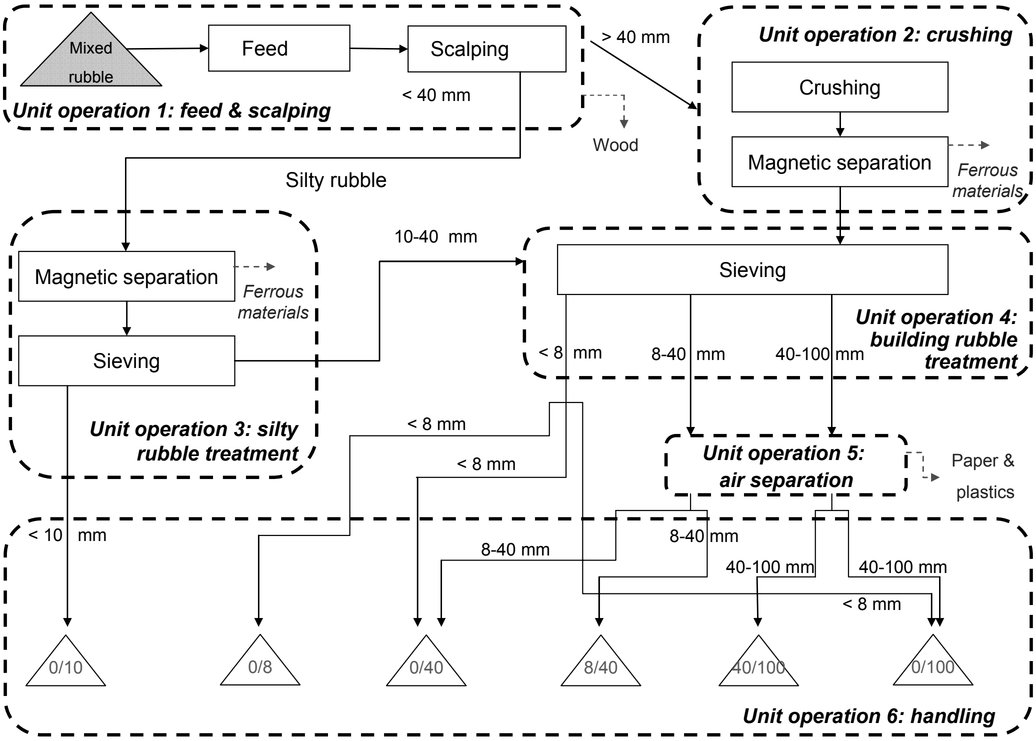

Figure 4. Main processes for the production of recycled aggregates at CAVIT plant.

3.2 Eco-profiles of recycled aggregates

When dealing with recycling processes, the from-cradle-to-gate philosophy must be turned into from-grave-to-cradle. In fact, as far as recycling operations are concerned, the raw materials are represented by scraps or waste otherwise addressed to landfill, which re-enter a further life cycle in substitution of virgin materials.

The eco-profiles of recycled building aggregates, some example of which are dealt with in Table 3, represent therefore the cumulative energetic and environmental interventions, from waste collection to the delivery of valuable secondary materials. On this point, it is worth noticing that among LCA practitioners it is a common understanding that scraps or waste do not hold any past energetic-environmental burdens when entering a recycling process. In other terms, waste materials do not take part in the allocation of environmental burdens relevant to the process that generated them.

With that in mind, the system that has generated the waste is credited of the waste that otherwise had to be disposed and the system that receives the waste is credited of the avoided virgin raw materials, but is charged with energy and ancillary materials used within the recycling process. Moreover, the system that makes use of recycled materials is credited by the energetic-environmental interventions that characterise the virgin building materials that are displaced.

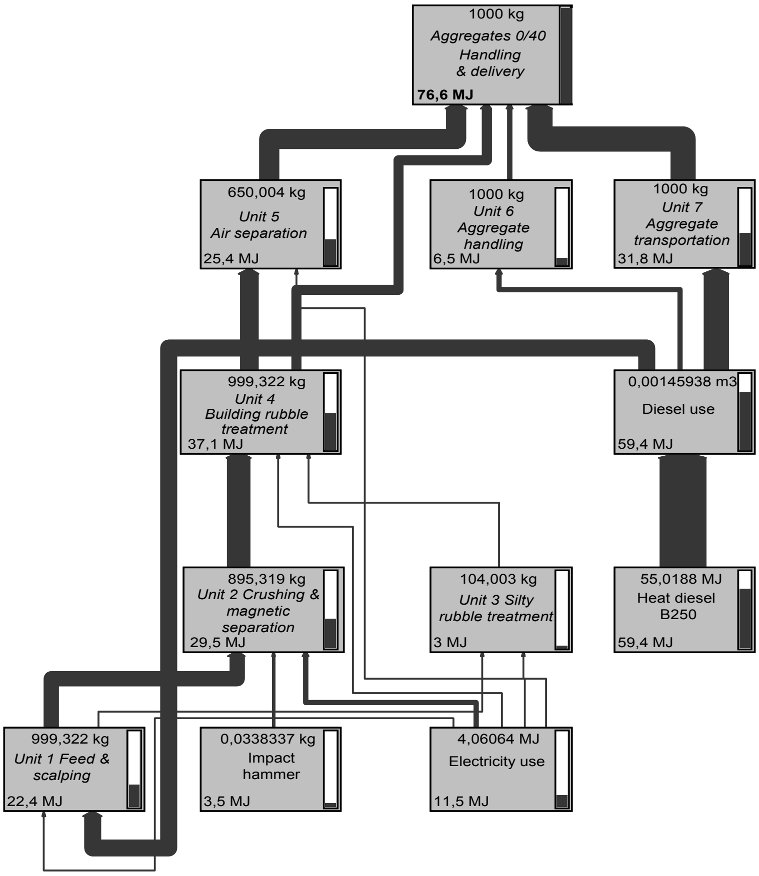

Figure 5. LCA model relevant to production and transportation of 0/40mm recycled aggregates at CAVIT processing plant.

In other terms, with reference to Table 2 and Table 3, the eco-profiles of recycled building aggregates tells us what are the energetic-environmental impacts associated with the recycling operations, while the eco-profiles of virgin aggregates tell us what are the gross benefits that can be achieved by recycling building aggregates. The difference between parameters relevant to virgin and recycled aggregates, also considering the mass yield of rubble processing, represents the net achievable benefit.

As it can be remarked by analysing Table 3, the production of 1 ton recycled aggregates, including all industrial processes starting from the feeding of rubble into the Cavit plant until the delivery of the final products to the customers, roughly corresponds to 67-77 MJ/t of Gross Energy Requirement and entails to an emission of 5-5.6 kg CO_2/t. Table 3 contains figures relevant to other impact indicators which characterize the different secondary raw materials. Average AP Acidification Potential is 2.34 mol H+equivalent, average EP Eutrophication Potential is 0.49 kg O_2 equivalent and the average Photochemical Smog Creation Potential is 0.08 g C2H4 equivalent. Moreover, the production of recycled aggregates corresponds to about 1 kg/t of waste.

Some more remarks can be done by analysing Figure 6 in which the contributions of recycling processing, bulk handling and transportation are emphasised. As far as energy use is concerned, recycling processing is responsible for 50% of the total energy consumption relevant to the production of average secondary aggregates, while handling and delivery are responsible for 8% and 42%, respectively. In case of greenhouse gas emissions, recycling processing is responsible for 47%, while handling and delivery are responsible for 9% and 44%, respectively.

Table 3. Main impact indicators representative of recycled building aggregates eco-profiles, CAVIT 2002.

From-cradle-to-gate Potential Environmental Impacts (data per 1 ton)	Unit	0/10 mm	0/8 mm	0/40 mm	8/40 mm	40/100 mm	0/100 mm	Average Cavit 2002	Average Cavit 2002
		Processing + handling + delivery 15km							(no transport)
Energy Resources, GER	MJ	66.9	75.4	76.6	77.3	77.3	76.8	76.3	44.5
Global warming, GWP CO_2 eq	kg	5.0	5.5	5.5	5.6	5.6	5.5	5.5	3.1
Acidification, mol H+ eq	mol	2.01	2.33	2.35	2.36	2.36	2.35	2.34	1.32
Eutrophication, O_2 eq	kg	0.48	0.49	0.49	0.49	0.49	0.49	0.49	0.23
Photochemical smog , C_2H_4 eq	g	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.04
Waste generation	kg	0.60	0.54	1.08	1.37	1.37	1.16	1.08	1.08

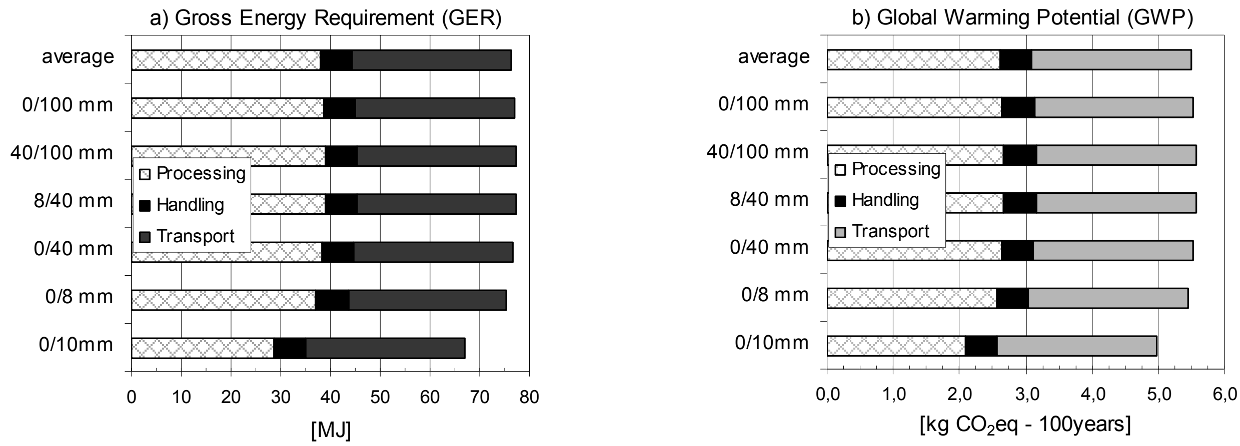

Figure 6. Contribution of processing, handling and transportation to the eco-profile of recycled aggregates.

4. Conclusions

The eco-profiles relevant to virgin aggregates and those relevant to recycled aggregates have shown that in both cases most of typical environmental and energy indicators have a comparable magnitude. The average GER relevant to natural aggregates is 109 MJ/t while recycled aggregates corresponds to 76 MJ/t. The average GWP relevant to natural aggregates is 6.6 kgCO_{2eq}/t, while recycled aggregates corresponds to 5.5 kg CO_{2eq}/t. On the contrary, AP, EP and POCP indicators relevant to natural aggregates are lower than those relevant to recycled aggregates. On the average, production of natural aggregates corresponds to a waste generation of 0.3 kg/t, while recycled aggregates produce 1.1 kg/t waste subsequently to recycling operations. However, recycling 1 ton of secondary aggregates avoid the landfill of about 1 ton of inert waste and its subsequent impacts. One more important consideration is that relevant to the remarkable contribution of transportation to the final energetic and environmental impacts: almost 45%. All this considered, it is worth to emphasise once more that when comparing natural and recycled aggregates, it must be proved that the recycling process is both economically and environmentally sustainable, in comparison with the production of natural aggregates. The results of the present research have confirmed that natural aggregates and recycled aggregates must not be considered as competitors but, on the contrary, their jointly use must be considered strategic in different sectors of the construction industry.

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