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ORIGINAL PAPER

Resources Optimization and Sustainable Waste Management in Construction Chain in Italy: Toward a Resource Efficiency Plan

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Abstract

The aim of this paper, by focusing on the construction chain, is to provide a functional-cognitive framework for orienting the use of all the available resources including raw materials, products and by-products but also residues and wastes in order to support national resource efficiency policies, to identify potential actions and to achieve resources efficiency and sustainable waste management within the entire supply chain. A material flow analysis (MFA) has been developed, on a national basis in Italy, and extended to the whole chain of construction and quarrying activities as a tool to develop the cognitive approach using the most recent data on production, sale and import–export, and to establish the potential domestic demand for each product. Waste production, current management and the potential of reuse within the chain have been investigated for several categories of wastes. The potential substitution of raw materials by residues produced in other industrial sectors has been also investigated, identifying their current reuse rate, the potential not yet exploited as well as the operational constrains and the critical issues. From this analysis enormous potentialities emerge for waste valorization and raw material substitutions that nowadays are not adequately exploited. Significant efforts, in term of national policies and strategies are needed to effectively shift towards a full resources management efficiency and circular economy development.

Keywords Construction chain · Resource efficiency plan · Material flow analysis · Construction and demolition waste · Circular economy

Statement of Novelty

This research fully supports the European directives and policies implementation on sustainable waste management strategies and circular economy in one of the most strategic waste production sector. The novelty of the approach lies in the material flow analysis carried out on a national basis, that covers the whole chain of construction activities and expands to other sectors, with the aim of developing a comprehensive and quantitative evaluation of the opportunities not yet exploited in waste recycling and raw materials substitution in the field of construction materials. The reported research will have impacts in addressing national policies and strategies in those sectors where further efforts are urgently needed to implement a strategic resource efficiency plan, within a sustainable construction waste management.

Introduction

Improving resource efficiency, environmental performance and business opportunities are some of the key objectives of the EU Construction 2020 strategy [1]. The construction sector and its value chain has been individuated in the circular economy package [2] as a key sector on which addressing efforts and specific actions for the circular economy implementation.

The construction and use of buildings in the EU account for about half of all extracted materials [3] and energy consumption [4] and about a third of water consumption [5]. A large amount of natural aggregates is produced and utilized every year in the construction sector: almost 2.6 billion tons in Europe and almost 150 million tons in Italy [6].

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Due to large quantities of construction raw materials produced and consumed, there is a need to improve the overall sustainability performance, and to ensure a higher proportion of recycling.

The sector also generates about one-third of all the produced waste [7] being associated with environmental pressures that arise at different stages of a building's life-cycle including material extraction, the manufacturing of construction products, building construction, use, renovation, demolition and the management of building's waste. Huge amounts of wastes, with the higher percentage still landfilled [8], are produced in quarries and processing plants (700 million tons every year in Europe) [9], as well as in construction and demolition stages (870 million tons per year in Europe representing the 40% of special wastes [10]).

Such an impressive amount of wastes and residues can potentially represent an enormous source of secondary raw materials if properly valorized [11] also through ecosystem innovation approaches such as the industrial symbiosis [12, 13] and methodologies for waste management and transportation costs reduction [14].

Developing actions for recycling and recovery of valuable raw materials from complex products, buildings and infrastructure, and other waste streams is one of the objectives individuated by the European innovation partnership (EIP) on raw materials in the strategic implementation plan (SIP) [15].

Interesting opportunities are offered by the recycling of quarrying and stone residues [16] and CDW [17, 18]. As the current average recycling rate of CDW for EU-27 is only 47% [19], increasing it, is nowadays not only an opportunity for virgin raw materials substitution, but first of all a necessity to meet the ambitious goal of 70% of recovery imposed by the 2008/98/EC Directive. Other interesting opportunities of natural raw materials substitution in construction sector are offered by industrial wastes as incineration bottom ashes [20–26], steel slags [27, 28], end of life products (e.g. crub tyre rubber [29, 30]) and automotive shredder residue (ASR) [31–33]. Even if several of these alternatives for raw materials substitution, have been widely investigated from a technical and economic point of view, the substitution rate of virgin raw materials with residues or valorised waste streams seems to be irrelevant also because of several and critical issues: lack of demand for recycled materials; distrust on the quality of recycled materials; lack of reliable criteria to demonstrate the qualification of by-product or the end of waste status; and finally lack of reliable data and monitoring on resource production and consumption and on waste flow extended to the lifecycle of material products which to elaborate a sector planning.

Keeping account of the resource inputs, extraction and consumption, as well as of the outputs (intended as the produced waste) is a fundamental step when planning actions based on resource efficiency and conservation. In this framework the material flow analysis/accounting (MFA) represent a valuable method of quantifying flows and stocks of materials or substances in a well-defined system. Recently, the MFA and derived indicators focusing on the whole economy have been established as the most widespread tools useful for monitoring the vast range of issues related to the consumption of materials. MFA indicators can enhance the understanding of the material basis of the economy and give an insight into how an economic system interacts with natural resource and material flows. MFA further contributes to trade policies by demonstrating the dependencies of countries on resources. In addition to national accounting of material flows, MFA has been increasingly used as a basis for analyzing and planning waste management and recycling systems [34, 35] from abroad and by monitoring the implications of trade and globalization in terms of shifts of environmental pressure between countries and world regions.

Methods for calculating and analyzing MFA indicators on the whole economy are quite standardized and they are calculated by a range of statistical offices (Eurostat, Istat). However it is difficult have disaggregated values for different sectors and materials.

An analysis based on sectoral and material disaggregation, both at national and at regional level could be very useful to shows material flows between the different sectors along the and beyond the construction products lifecycle.

This paper, through a MFA carried on a national scale, that covers the whole chain of construction and quarrying activities and expands to other sectors, aims to developing a comprehensive and quantitative evaluation of resource flows, waste production and recycling rate, in order to underline the opportunities yet or not yet exploited in terms of waste recycling and raw materials substitution in the field of construction materials.

Methodology

A MFA has been implemented on a national basis (Italy) and extended to the whole chain of construction and quarrying activities, as well as to other conterminous sectors, with the aim of characterizing and quantifying both the overall waste production, the actual demand for several raw materials classes and their potential substitution rate in order to have a baseline supporting national initiatives and policies on resources efficiency and waste management in this sector and related ones.

Figure 1 describes the whole framework including all the investigated sectors and its boundaries. All the relevant materials flows are reported with references to the following tables included within the work.

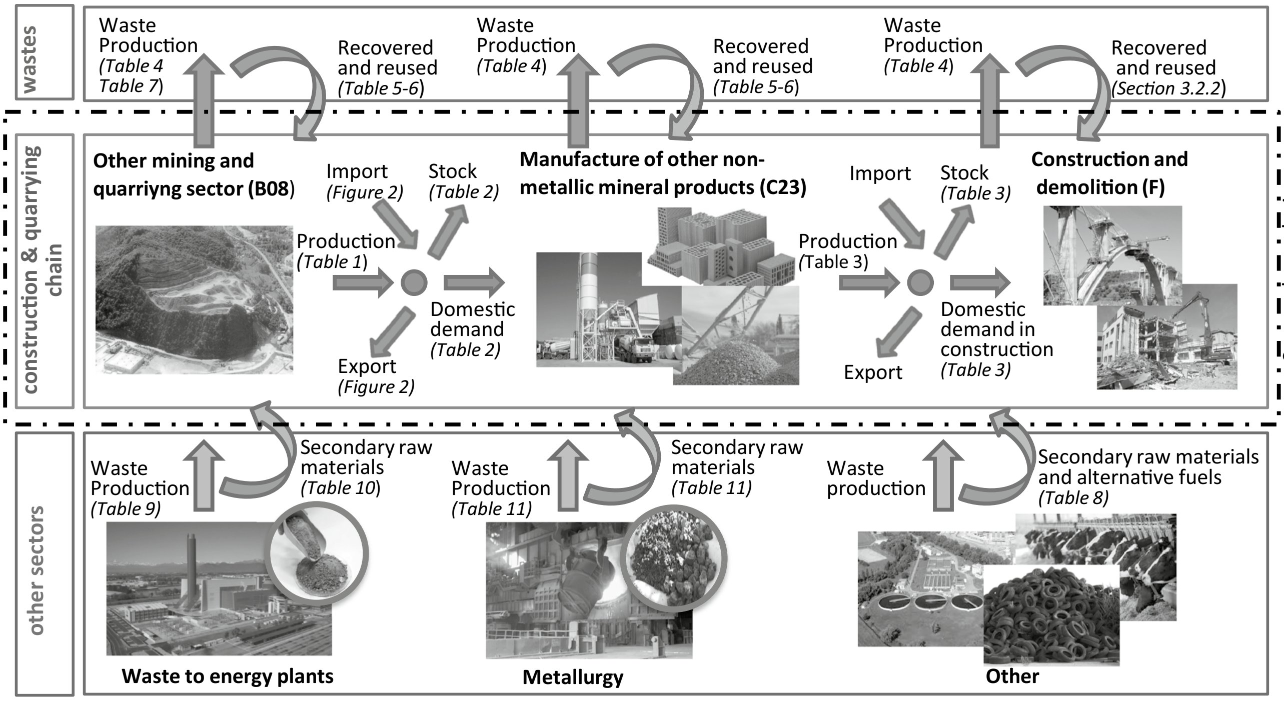

Fig. 1 System boundaries, involved sectors and resources flows (materials, wastes and secondary raw materials) within the chain and from other sectors

The investigation encompasses all the sectors in a life cycle perspective from cradle to cradle, starting from the raw material production, moving through the manufacture of building products, the construction of buildings and infrastructures up to the final demolition and related material recycling:

- Quarrying sector (NACE code B8.1, B8.9.9)
- Manufacture of building products and materials (NACE code C.23 "Manufacture of other non-metallic mineral products")
- Construction and demolition (NACE Codes F42 "Civil engineering" and F.43 "Specialised construction activities")

Other sectors, including waste to energy plants and metallurgy, have also been investigated in term of waste production and recycling as potential substitutes of virgin construction materials.

As reported in Fig. 1, the following activities have been carried out according to the proposed MFA:

(1) *Resource flow analysis*. Using the most recent available data on production, sales and import–export, an analysis of resources used throughout the chain was carried out. For each investigated sector and product, the domestic demand and the stored stock have been evaluated over the entire production system as reported in Tables 1 and 3.

(2) *Evaluation of wastes production, management and reuse rate.* Overall wastes production (i.e. from the mining activity and processing of natural stones, from cement and concrete production, and from construction and demolition) and its actual management have been estimated together with the actual recycling rates and their not-fully-exploited potential throughout the chain. Specific focus areas included:

- Recovery of residual sludge from stone processing.
- Recovery of C&D waste.

(3) *Individuation of raw material potential substitution opportunities with residues and wastes produced in other sectors.* Potentialities of substitution of raw materials with residues originated by other activities have been investigated with specific focus on;

- Material and energy recovery in cement industry.
- Reuse of MSWI bottom ash.
- Reuse of steel slag.

Production and import–export data have been elaborated on the basis of official data from the Italian Institute of Statistics (ISTAT). Information regarding waste production and management have been collected from official reports of the Italian Institute for Environmental Protection (ISPRA) and from public reports of industry associations.

Domestic demand, evaluated for both raw materials and construction products, has been assumed as coinciding to the domestic consumption (internal sold production—export + import). The difference between volumes produced and volumes sold represents the stock stored in the production system.

Results and Discussion

Resource Flow Analysis and Domestic Demand

Quarrying Sector

Demand for construction raw materials is closely related to the number of approved civil engineering projects, new buildings and renovation activities. The Italian quarrying industry total production in 2013 is around $167,395 \times 10^3$ tons, of which $50,205 \times 10^3$ are ornamental stones, $116,225 \times 10^3$ are building aggregates and 964×10^3 are bitumen and natural asphalt materials (Table 1).

The largest production concerns aggregates such as sand and gravel (on average 69% of total production) with a significant reduction in recent years due to the economic crisis.

Table 1 Production and sold product classified on the basis of typology in the "Other mining and quarrying" sector (Nace code B.8) in Italy

NACE code	ProdCom code	Product type	Production (10^3 t)			Product sold (10^3 t)		
			2011	2012	2013	2011	2012	2013
B08.11	08.11.11.33 08.11.11.36	Marbles and travertine	5775	4207	5290	5643	3921	4917
	08.11.11.50	Limestone stones, alabaster	8207	6925	9865	5987	6760	9627
	08.11.12.33 08.11.12.36	Granite	2541	1176	1305	2441	1090	1161
	08.11.12.50	Sandstone	315	279	241	153	146	108
	08.11.12.90	Other construction stones	1549	1281	1190	1462	1205	1112
	08.11.20.30	Gypsum stone	3643	3201	3192	3491	2962	2854
	08.11.20.50	Limestone (non-inert)	38,159	26,863	27,435	22,976	14,291	16,608
	08.11.30.10	Clay			910			872
	08.11.30.30	Dolomite	1422	807	735	1335	717	658
	08.11.40.00	Slate	56	59	42	50	59	41
B0812	08.12.11.50	Siliceous sand	14,959	14,123	12,510	14,143	12,935	11,783
	08.12.11.90	Construction sands	80,694	62,296	45,124	74,199	54,973	40,732
	08.12.12.30	Crushed stones for concrete, road and other constructions	86,548	75,406	49,076	78,247	66,576	41,735
	08.12.12.50	Granules and marble powders	6717	3835	3527	5901	3410	3169
	08.12.12.90	Granules and marble powders (except marble)	223	214	233	182	178	188
	08.12.13.00	Mixed waste	420	352	326	405	341	275
	08.12.21.60 08.12.22.10 08.12.22.50	Clays	5544	4444	5429	4083	3262	4459
B0999	08.99.10.00	Bitumen and natural asphalt	1737	1216	964	1753	1229	953
Tot ornamental stones (B08 11)			61,668	44,799	50,205	43,539	31,151	37,957
Tot aggregates (B08 12)			195,105	160,670	116,225	177,160	141,675	102,340
Tot bitumen and natural asphalt (B09 99)			1737	1216	964	1753	1229	953
Total			258,510	206,685	167,395	222,452	174,055	141,250

Ornamental stones' mining has been less affected by the crisis, thanks to the contribution of export.

Among the ornamental stones, the largest production refers to non-crushed limestone (55% in 2013), followed by constructional limestones including alabaster (20% in 2013), marble and travertine (11% in 2013).

In 2013, 88% (102,340 × 10^3 tons) of aggregates and 76% (37,957 × 10^3 tons) of ornamental stones production were sold in Italy. By comparing these data with those referring to production and import–export (Fig. 2) it is evident a significant amount of unsold stocks.

Italy, and more in general Europe, is self-sustaining for aggregates production. Imports are limited, with the exception of Belgium and the Netherlands.

Figure 2 shows the import–export data in the last years. In 2014, the Italian stone industry exported more than 4 million tons of marble, granite, travertine and other stones, both raw and carved, for a value of almost 2 billion euros. The detail is shown in Fig. 2.

Raw marble leads the Italian export (1.3 million tons for a total value of 331 million Euro) followed by carved marble (892 thousand tons for a total value of 936 million Euro), carved granite (570 thousand tons for a total value of 535 million euros) and raw granite (136 million tons for a total value of 36 million euro).

Despite the exports, in 2014, Italy imported almost 1.5 million tons of marble, granite and other stones for a total value of 395 million euro.

The main indicators used in the proposed MFA are reported in Table 2. Domestic demand for construction raw materials has been calculated on the basis of data on production and sales (Table 1) and import–export (Fig. 2) reaching the value of 138 millions of tonnes in 2013 (almost 99 million for aggregates and 36 million for ornamental stones).

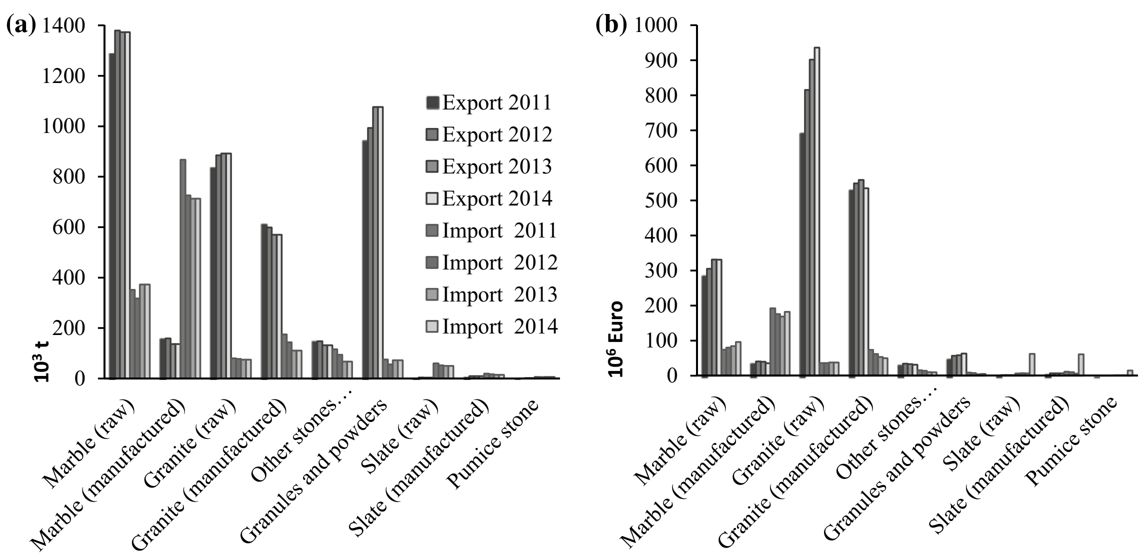

Fig. 2 Import–Export for natural stones in Italy: **a** weight, **b** value

Table 2 Domestic demand and stock stored in production system for construction minerals and ornamental stones in 2013 in Italy

Product type	Production (10^3 t)	Sold production (10^3 t)	Import (10^3 t)	Export (10^3 t)	Domestic demand (10^3 t)	Stock (10^3 t)
Ornamental stones[a]	50,205	37,957	1340	3225	36,072	9024
Aggregates (silt, sand, gravel, fract. stones, slags)[b]	112,465	98,984	0	0	98,984	13,481
Aggregates (granules and powders)[c]	3761	3357	51	1047	2361	0
Bitumen and asphalt	964	953	0	0	953	11
Total	167,395	141,250	1391	4272	138,369	22,516

[a]Sum of ProdCom codes 08.11.11.33; 08.11.11.36; 08.11.11.50; 08.11.12.33; 08.11.12.36; 08.11.12.50; 08.11.12.90; 08.11.20.30; 08.11.20.50; 08.11.30.10; 08.11.30.30; 08.11.40.00

[b]Sum of ProdCom codes 08.12.11.50; 08.12.11.90; 08.12.13.00;08.12.21.60; 08.12.22.10; 08.12.22.50

[c]Sum of ProdCom codes 08.12.12.50; 08.12.12.90

A large amount of this production, almost 22.5 millions of tonnes (of which 13.5 million of aggregates and 9 millions of ornamental stones) has not found place on the market yet, remaining as stock stored in the production system. No stocks were accumulated in 2013 for aggregates (e.g. granules and powders) as the demand was satisfied with stocks from the previous years.

Manufacture of Building Products and Materials

Table 3 shows data on the "Manufacture of other non-metallic mineral products" sector (C23), focusing on the Italian production of the last years and the corresponding sold volumes.

The total production of the sector amounted to 164,204 thousand tonnes in 2013, with a considerable amount of ready-to-use concrete ($81,482 \times 10^3$ tons) and cement ($38,805 \times 10^3$ tons) followed by the manufacture of other non-metallic minerals (4312×10^3 tons), manufacture of lime products (9518×10^3 tons) and marble, stones and minerals processing (6424×10^3 tons).The crisis in the construction sector inevitably reflects in the productive sectors along the chain. Especially in the case of primary construction materials as cement, lime and concrete, it is dramatically evident the significant lowering trend of production over the last years (−25%). Sold production follows the same trend of production (−24%) but with an additional reduction of 10%.

Domestic demand for construction products, which represents the driving force in the construction sector, has been calculated and reported in Table 3 (column 8) considering the available data on imports and exports. Except for ready-to-use concrete and mortar, domestic production meets domestic demand with a slight overproduction that finds no place on the market (column 8 and 9 in Table 3). On the other side the most relevant stock is referred to cement.

Wastes Production and Potential Reuse Within the Construction and Quarrying Chain

Table 4 shows the wastes production from 2012 to 2014 in the building and quarrying chain. The main production of waste arises from construction and demolition activities.

Table 3 Production and sold production classified for product type in "Manufacture of other non-metallic mineral products" sector (Nace code C.23) in Italy

Product type	Production (10^3 t)			Sold production (10^3 t)			Domestic demand (10^3 t)	Stock (10^3 t)
(Manufacture/production of)	2011	2012	2013	2011	2012	2013	2013	2013
Refractory material	852	919	801	832	900	762	762	39
Bricks and tiles	647	730	576	666	691	556	556	20
Ceramic sanitary ware	67	50	32	66	49	31	31	1
Insulators	3	3	6	3	3	6	6	0
Other ceramic prod. for technical use	0	1	1	0	1	1	1	0
Other ceramic prod.	324	252	28	308	242	26	26	2
Cement	56,396	46,532	38,805	35,323	28,775	24,230	24,230	14,576
Lime	5160	5489	3907	4254	4354	3412	3412	496
Lime products	12,604	12,389	9518	12,423	12,297	9368	9368	150
Concrete ready for use	109,842	99,812	81,482	109,783	99,514	82,909	84,337	0
Mortar	4258	3752	3132	4246	3755	3150	3167	0
Other prod. concrete, lime, asbestos	4279	3760	4312	3844	3445	3929	3929	383
Other stones and minerals marble	6695	6639	6424	6244	6203	6048	6048	376
Other non-metallic minerals	18,185	16,278	15,180	17,048	15,224	13,517	13,517	1664
Total	219,313	196,608	164,204	195,039	175,454	147,944	149,389	17,705

Table 4 Waste production in the building and quarrying chain in Italy

Nace code	Waste production (10^3 t)		
	2012	2013	2014
B.08	193.4 (3.4 HW)	139.1 (2.6 HW)	197.8 (4.2 HW)
C.23	2988.7 (108.6 HW)	2842.8 (66.5 HW)	2779.5 (43.3 HW)
F (C&D waste)	51,629	47,940	51,491

About 50 million tons of CDW (40% of special wastes) are produced every year in Italy [3]. The manufacture of other non-metallic mineral products sector (C.23) contributes with almost 3 million tons of wastes (2% of special wastes) and the quarrying sector (B.08) with almost 200 thousand tons. This last amount does not include specific residues (e.g. the discarded blocks with defects affecting their marketing) that are not considered wastes as they are easily re-used. In the processing of ornamental stones there is a considerable production of sludge and solid waste from the finishing activities (sanding and/or polishing). This residue is not effectively reused although several solution for its valorisation and reuse are already practicable and its production is significant. As an example the average production of sludge in two important Italian extraction basins, such as the Val d'Ossola and the Luserna, is as high as 70 and 16 thousand tons per year respectively [36]. These data highlights as additional optimization efforts should be addressed to improve recovery rates and reuse of these residues (i.e. CDW, sludge from stone processing) that are currently managed as waste.

Recovery of Residual Sludge from Stone Processing

At present, the recovery rate of residual sludge from stone processing in Italy is equal to 10%. The chances for their valorisation and reuse depend on their specific composition [which is correlated to the stones' typology (i.e. marble, granite, basalt etc.)], processing activities (cutting and finishing) and wastewater treatments [11].

Tables 5, 6 show the potential for recovery and reuse for different sludge, the specific standards and the required chemical-physical properties. Sludge of marble or carbonate rocks can replace the quarry limestone. Several industries can use calcium carbonate in processing plastic, paper, rubber, ceramic, cement, concrete, animal feed, fertilizer, glass, steel, paints, medicines, plasters and coatings industries, and finally in agriculture as a correction of acidity.

Thanks to its chemical and mineralogical properties and its very fine granulometric distribution, carbonate sludge, may also be used as low-cost mineral filler to improve the final product characteristics in several applications. At present it covers about 50% of the low-cost filler and reinforcing materials market and it may contribute to the composition of finished products by about 10–50% by weight in the case of thermoplastic materials. Higher percentages can be used for thermo-setting materials. The greatest potential for its reuse is in the molded or extruded products for which very high quality standards are not required. An example can be represented by PVC pipes not intended to withstand high pressures or thermal stresses, such as those used in construction or for the protection of electrical circuits, which may contain charge up to 60% by weight of carbonate sludge. For the same reasons, carbonate sludge is one of the first alternative raw materials for building products, such as impermeable bituminous seals and superficial layers of bituminous conglomerate for road pavements.

Another important chance of using marble sludge is for the abatement systems of sulfur oxides (SO_2, SO_3) from combustion processes. This application gains additional economic interest when the transport costs of sludge at the nearest thermal power plant is lower than the transport and disposal costs at landfills. The abatement processes are achieved by contacting the gaseous emissions with suitable reactants capable of retaining SOx by absorption or chemical reaction. Limestone, used as such, or calcined (CaO) or calcined and hydrated ($Ca(OH)_2$), is appropriated to this function for its ease of combining with SOx, matching high abatement efficiencies at low cost.

Carrara marble sludge, made up of almost pure calcium carbonate, can be used as an integrator for animal feed, in percentages between 7 and 10% of the total mass.

For sludge resulting from the processing of siliceous stone, such as granite, convenient re-use is related to the production of agglomerated and bricks because of the ability of sludge to improve the mechanical properties of brickwork. Siliceous sawing sludge can be used to reduce the tendency of certain clays used in the manufacture of bricks to have high retraction and deformation/cracking during drying operation. The sludge to be added must meet a wide range of characteristics (humidity, chromatic variation, water absorption). The biggest problem is the water absorption that limits the use of sludge as a smear at 2%, while the withdrawal rates are always on average acceptable.

The main obstacle to a wide reuse of sludge from stone processing is the lack of confidence offered by the legislation with special reference to the ambiguous definition of these residues (waste or by-product). The difficulties encountered

Table 5 Recovery and reuse options for all types of sludge from stones processing

Reuse option	Standards
Fine aggregates (fillers) to be used in the production of cement or bituminous conglomerates	UNI EN 13043
Sub-base in road construction	UNI EN 13055-2
Environmental restoration	Leaching test (DM 186/2006)
Landfill cover	Leaching test (DM 186/2006)

Table 6 Recovery and reuse options of sludge from stones processing for different composition

	Reuse option	Composition	Humidity	Granulometry
White and colored marble sawmill	Agriculture, land deacidification	Appropriate	Appropriate	Appropriate
	Cement production	Appropriate	Appropriate for wet process. Required dewatering (with filter press) for dry process	Appropriate
	Production of kitchen plans	Appropriate	≤ 1%	0.6–0.35 µm
	Pitches for PVC materials	$CaCO_3 > 90\%$	≤ 1% circa	Appropriate
	Absorption of acid refluxes	Appropriate	Appropriate	Appropriate
	Flue-gas (with SO_2) treatment	Appropriate	Appropriate	Appropriate
White marble sawmill (high $CaCO_3$)	Paper production	$CaCO_3 > 90\%$ and without colored impurities	Appropriate for "marmettola" < 1% for dry process	Appropriate
	Production of water-based paints and varnishes	$CaCO_3 > 90\%$ ed assenza di impurezze colorate	< 1% for dry process	Appropriate
	Production of plastics in polypropylene	$CaCO_3 > 90\%$ $Fe \leq 0.02\%$	≤ 1%	Appropriate
	Soda production	$CaCO_3 > 90\%$ FeO_2, SiO_2, $Al_2O_3 < 3\%$ $MgCO_3 < 6\%$	≤ 1%	10–15 mm compacted
	Metallurgical sector	Appropriate	≤ 1%	6–30 mm compacted
Mixed (marble, granite) sawmilland siulicatic	Tetrapod	Appropriate	< 15%	30%: 50–250 µm 50%: 250–500 µm 10%: < 10 µm
Granite and siliceous stone sawmill	Production of agglomerated stones (cobblestones, flooring and tiles)	Appropriate	< 15%	30%: 50–250 µm 50%: 250–500 µm 10%: < 10 µm
	Smelling for bricks production	Appropriate	< 15%	
	Environmental restoration, landfill coverage	Appropriate	Appropriate	Appropriate

by the small companies in demonstrating the by-product qualification still results in a high recourse to disposal.

Recovery of C&D

Despite an apparently virtuous picture on the recovery percentages drawn from the official estimates sent to the EU from Italy [3], the goal imposed by Framework Directive 2008/98/EC, implemented by the 205/2010 Legislative Decree, is far from being achieved. According to estimates by ANPAR (National Association of Recycled Aggregates Manufacturers), the recovery rate is still around 10% and, as a consequence, the amount of recycled C&D waste amounts to around 5 million tonnes per year. If we consider that about 116 million tonnes of aggregates were produced in 2013 in Italy, and the domestic demand is almost 100 million tons (Table 2) it is clear that almost all the aggregate demand is met by natural materials (about 95%) and the current rate of replacement of virgin raw materials with CDW achieves only 5%.

A recurring obstacle to recycling and re-using CDW is concerned to the quality of C&D recycled materials. This lack of confidence reduces and restricts the demand for C&D recycled materials, which, in turns, inhibits the development of CDW management and recycling infrastructures. The second main obstacle is the lack of appropriate and specific legislation and recycling criteria in the country.

Potential for Replacement of Raw Materials with Residues and Wastes Produced in Other Processes

Material Recovery in Cement Industry

Every year, a large amount of raw materials (25 million tons) are consumed by the cement industry [37] with a consequential high contribute of mining activity to the environmental footprint.

Mineral rocks can be easily partially replaced by alternative materials in the production of low clinker content cement. These materials are generally non-hazardous waste and by-products from different industrial processes. Steel and metallurgical industry can provide wastes from steelworks, rolling chips, melting slags, residues of ores and incineration bottom ashes; heavy ash in addition to desulphurisation chalks can also origin from waste incinerators; water processing and purification produce suitable sludge; pyrite ashes, inorganic waste and exhaust catalyst come from chemical industry; mining and construction sectors provide several inert wastes (without asbestos), marble and granite processing scraps, rock residues; finally powders can be collected within the same cement production recycled and re-introduced into the process.

Table 7 shows the most recent data on raw materials consumption and alternative materials utilized for cement production. In 2015 [38] more than 850,000 tons of recovered materials, mainly constituted by coal, biomass and waste combustion ashes (418,000 tons), steel industry waste (181,000 tons), chemical chalks (173,000 tons) and quarrying waste (63,000 tons) have been used. Bearing in mind that in Italy every year more than 120 million tons of non-hazardous special wastes are produced [3], cement industry employs, at the present, less than 1% of them. The actual raw material substitution rate is limited to a few percentage points (6.5% in 2015) but it could substantially raise thanks to the high availability of secondary raw materials not utilized yet, as, for example, metallurgical waste (1600,000 tons produced of which only 330,000 reused) or marble quarrying and processing wastes (10,000 tons of which only 18 reused) [25].

Table 7 Raw materials, non-hazardous waste an by-product used in cement production and substitution rate in 2015 in Italy

Item	Amount (t)	Total (t)
Mineral rocks		
Clay	1,911,533	25,487,111
Marl	9,532,180	
Limestone	14,017,911	
Chalk	510	
Pozzolan	510	
Shale	255	
Other	24,213	
Recovery materials from non-hazardous waste		
Siderurgic waste	181,085	860,654
Chemical waste	21,326	
Quarrying waste	63,171	
Refractory waste	2897	
Coal, biomass and waste combustion ashes	418,404	
Desulphurisation chalks	173,088	
Others	683	
Industrial by-products (not classified as waste)	667,606	667,606
Raw materials substitution rate	6.5%	

Reuse of MSWI Bottom Ash

The recovery of wastes derived from waste-to-energy (WTE) processes is one of the options that, in recent years, thanks to the continuous technological evolution, has a major strategic role to drastically reduce final disposal at landfill while increasing the amount of recyclable materials [25].

Proved treatment technology allows to almost entirely recycle these waste in the cement and concrete industry [39] and to extract aluminium and other metals [40] as shown in Fig. 3.

In Italy there are 44 incineration plants for municipal solid waste (MSW) and solid recovered fuel (SRF). Table 8 shows recent data on wastes incinerated and residues in WTE plants in Italy.

The total waste incinerated in Italy amounts to about 6.3 million tonnes, of which almost 2.7 million are undifferentiated urban wastes, about 1.7 million tonnes are constituted by the waste dry fraction, more than 900,000 tonnes by SRF, 977,000 tons by special wastes of which nearly 39,000 tons are sanitary waste. Special hazardous wastes, mainly of health-care origin, amount to more than 52,000 tonnes.

In 2014 wastes addressed to incineration consist for 72.1% of non-hazardous refuse and for the remaining 27, 9% of hazardous waste. Wastes generated from incineration plants are about 1.4 million tonnes and account for 22.4% of the incoming materials [10]. Typical produced residues are non-hazardous bottom and ashes (69.6%, i.e. about 980 thousand tonnes) that represent the fraction recoverable in construction sector. Table 9 shows its current recovery and disposal rates.

Regarding the materials recovered from the treatment in 2010 approximately 3% is made up of ferrous metals and 0.1% by recycled non-ferrous metals. The remaining approximately 97% consists of mineral material that is mainly recovered as a cement additive or for the production of concrete in place of natural gravel.

Reuse of Steel Slag

The Best Available Techniques Reference Document for Iron and Steel Production [42] emphasizes the importance of the reuse of steel slag in the field of civil works and road constructions.

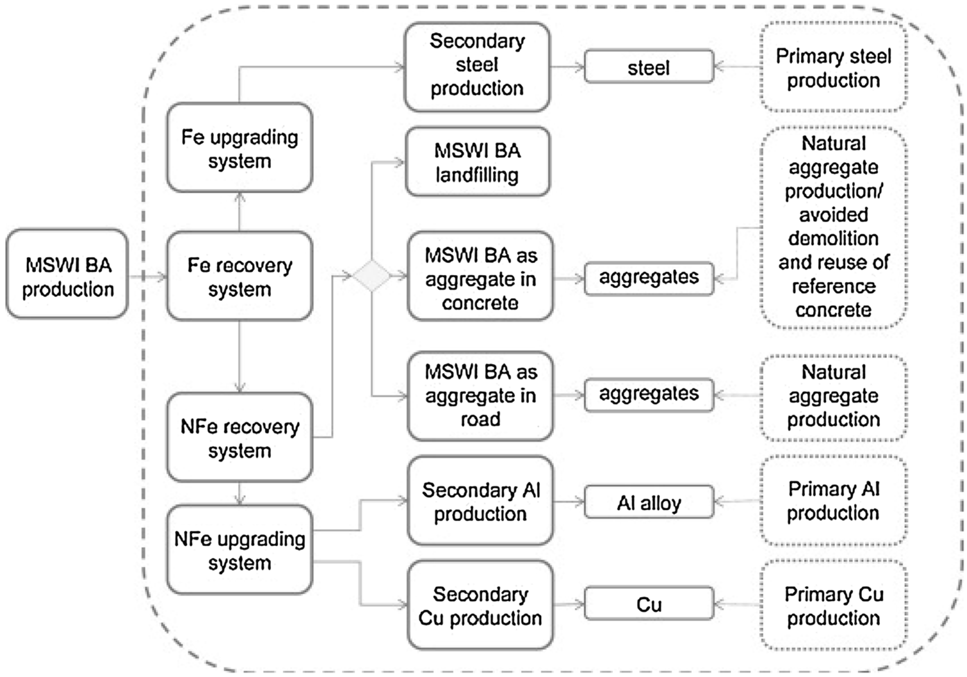

Fig. 3 Full recovery scheme of MSWI bottom ashes

Table 8 Incinerated wastes and waste production in incineration plants in 2014 [10]

Plants	Treated waste (10^3 t)	Waste incineration residues (10^3 t)							% On incinerated waste
		From fuel gas treatment section	Hazardous bottom ash, fly ash and slag	Non-hazardous bottom ash, fly ash and slag	Sand	Liquid wastes and sludge	Ferrous metals	Total	
44	6278	197	183	980	14	14	19	1407	22.4

Table 9 Slag and bottom ash recovery rate and typologies of the recovery products

Geographic area	Disposal[a]		Recovery[a]		Type of recovered materials (%)[b]		
	(10^3 t)	(%)	(10^3 t)	(%)	Inert	Ferrous metals	Non-ferrous metals
Nord	105.6	14.6	615.2	85.3	96.4	3.5	0.1
Centre	30.6	30.8	68.6	69.2	97.9	2.0	0
South	44.9	26.0	129.6	75.0	97.8	2.0	0.2
Total in Italy	181.0	18.2	813.4	81.9	96.7	3.2	0.1

[a]Elaboration from [10]

[b][41]

In order to identify sustainable re-use in the construction sector, the available scrapping characteristics, should be correctly considered as well as the different reuse-options (cement, cement conglomerates, bituminous conglomerates, road signs, etc.), the regulations (waste, by-product, end of waste) and the technical standards require by the industry.

Steel is basically produced by two distinct production processes: (1) the whole cycle, which makes use of raw materials such as mineral iron and carbon fossil, and (2) the electrical arc furnace cycle (EAF), which fuses iron scrap, exploiting the features of complete steel recyclability. The whole cycle for steel production (integrated works) essentially produces four types of steel scrap: (1) granulated blast furnace slag (GBS); (2) air-cooled blast furnace slag (ABS); (3) basic oxygen furnace slag (BOS); (4) steelmaking slag (SMS). Table 10 highlights the slag production and the recovery percentage for each destination (i.e. cement,

Table 10 Slag production and the recovery percentages for each destination in Italy

Slag	Production (10^3 t)	Recovered (%)	Cement (%)	Environ. restoration (%)	Internal reuse (%)	Concrete (%)	Asphalt (%)	Road ballast (%)	Road base (%)
GBS	2150	100	99.7	0.3	0	0	0	0	0
ABS	50	100							
BOS	1050	100	0	0	20	0	0	80	0
EAF–C	1900	75	0	3	0	27	11	15	44
EAF–S	400	75	13	1	0	29	53	0	4
SMS from EAF	700	75	9	3	30	33	5	2	18
SMS integrated works	330	100							
Tot. integrated works	3580	100	67	8	6	0	0	19	0
Tot. EAF	3000	75	2	3	3	28	13	12	38

environmental restoration, internal use, concrete, asphalt, road ballast and base) in Italy.

The analysis of the data (2010) shows an average production of more than 3.5 million tons per year of slag deriving from integrated works that is completely absorbed by the construction industry (less than 1% is disposed of). Most of the production consists of GBF which is reused prevalently for cement production and BOF used prevalently for road ballast. EAF slag amounts to about 3 million tons per year, of which 75% has been reused for road pavements (38%) and concrete (28%), while residual quantities for the construction of bituminous conglomerates (13%) and road ballast (12%). There are further opportunities for improvement in the reuse rate due to residual and undeveloped capacity of about 750 thousand tons of EAF slag per year.

Conclusions

The construction sector determines the extraction of large amount of raw materials and it is responsible for a consistent production of wastes throughout the life cycle. Improving resource efficiency will allow a reduction in environmental pressure and an increase of business opportunities. This paper, through a MFA at national level that has been extended to the whole life cycle, from the production of raw materials to the construction of buildings and infrastructure, presents an evaluation of the current state of natural resource utilization (raw materials) and waste production, as well as its disposal and reuse rate in substitution of natural raw materials in Italy as a representative case study. The results highlight the high domestic demand both for raw materials (138 million tons of construction minerals and ornamental stones of which almost 100 million of aggregates and 36 million of ornamental stones) and for manufactured building products (149 million tons of which 81 million of ready-to-use concrete and 39 million of cement).

Results also demonstrate that waste production in the overall construction and quarrying chain is considerable and should be sustainably addressed. The most consistent amount of wastes is produced during construction and demolition activities (about 50 million tons of CDW every year), whereas the manufacture of building products and materials contributes with almost 3 million tons and the quarrying sector with almost 200 thousand tons. The rate of substitution of virgin raw materials with valorised waste produced within the chain appears to be still low. Comparing the amount of recycled C&D waste, consistsing in around 5 million tonnes per year, to the domestic demand for aggregate of almost 100 million tons, it emerges as neary all the aggregate demand is met by natural materials (about 95%) with a current rate of replacement of virgin raw materials arrested at 5%.

The performed MFA has proposed also other options for raw materials substitution in construction sector, as offered by different industrial wastes. High reuse rates are achieved for the 6.5 million tons per year of steel slag (100% for integrated works slag) and for the 980 thousand tons per year of non-hazardous fly and bottom ash (81%) coming from MSWI. Cement industry, for example, is capable to use wastes from several production sectors both in terms of material and energy. The actual raw material substitution rate is limited to few percentage points (6.5% in 2015) but it could substantially raise thanks to the high availability of secondary raw materials not fully exploited yet. Although in the cement industry, alternative fuels are already utilized in substitution of traditional ones, the actual substitution rate (15%) is still too low if compared with the European average of 30% and the peak value of 60% achieved in some nations.

It is therefore clear that the potential in term of substitution of raw materials with residues and wastes is not adequately exploited and further efforts, in term of national policies and strategies are urgent to effectively move towards the full application of the circular economy in the sector.

The results of this study could be useful to address national policies and strategies in those sectors where most of the efforts are required.

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