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Construction and demolition waste best management practice in Europe

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ABSTRACT

Construction and demolition waste constitutes a large fraction of all the waste generated in Europe. Its specific impact can be considered rather low, but the large generated volume and embodied resource makes this waste stream an important focus of current European policies. The European Commission has proposed new targets and goals for this waste stream in the Circular Economy package, but, given the rather heterogeneous landscape of waste management practice across Member States, new approaches that take into account the entire value chain of the construction sector are urgently required. This paper synthesises core principles and linked best practices for the management of construction and demolition waste across the entire construction value chain. Systematic implementation of these best practices could dramatically improve resource efficiency and reduce environmental impact by: reducing waste generation, minimising transport impacts, maximising re-use and recycling by improving the quality of secondary materials and optimising the environmental performance of treatment methods.

1. Introduction

Currently, the European construction sector produces 820 million tonnes (megagram, Mg, or 1000 kg) of construction and demolition waste (CDW) every year, which is around 46% of the total amount of total waste generated according to Eurostat (Eurostat, 2017). The average composition of CDW shows that up to 85% of the waste is concrete, ceramics and masonry, although CDW can be heterogeneous depending on the origin, and may contain large amounts of wood and plasterboard (Monier et al., 2011; U.S. Environmental Protection Agency, 1998). In any case, CDW inorganic fraction is frequently characterised as "inert" due to lack of chemical reactivity at ambient conditions. Most CDW consists of excavated materials, which are considered to have a low environmental impact upon disposal. If excavated materials are excluded, around 300 million Mg of CDW were generated in 2014 at European construction sites (i.e. EU 28 new construction, demolition or refurbishment activities).

Construction and demolition waste is characterised by its high volume and weight but with probably the lowest environmental burden and the highest inert fraction per Mg of all waste streams. Although the specific environmental impact (per Mg) is low if compared with other waste streams, the associated environmental impacts of such a high amount of CDW is an important concern, mostly derived from its logistics and land occupation. Hence, the management of CDW constitutes a priority for most environmental programmes around the world, especially in Europe. In fact, the European Commission (European Commission, 2015a) has proposed that, by 2020, "the preparing for re-use, recycling and backfilling of non-hazardous construction and demolition waste *excluding naturally occurring material* defined in category 17 05 04" – i.e. soil (including excavated soil from contaminated sites) and stones not containing dangerous substances – "in the list of waste shall be increased to a minimum of 70% by weight". Remarkably, the definition excludes naturally occurring materials but introduces overall recovery targets, while some experts have recommended to introduce separate targets per fraction and to revise the definition of treatment operations, as backfilling (Arm et al., 2014; BioIS, 2016). There is also some concern on the use of weight percentages, since waste managers may focus on the dense mineral fractions rather than on other fractions with potentially higher potential environmental impact (Arm et al., 2014).

Abbreviations: BaU, business-as-usual; BEMP, best environmental management practice; CEN, *Comité Européen de Normalisation*; CO_2e, equivalent CO_2 emissions; CDW, constructionand demolition waste; EMAS, eco-managementand audit scheme; EN, European norm (European standards); PCBs, polychlorinated biphenyls; RA, recycled aggregates; RCA, recycled concrete aggregates; SWMP, site waste management plans; WRAP, waste and resources action programme

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Novel solutions, instruments and approaches are required for the management of CDW. While a recycling rate of 70% for non-hazardous construction and demolition waste can be considered an ambitious target in certain countries, the industry has noticed that national circumstances are heterogeneous across European Member States and that such a target lacks incentive for the industry of those countries or regions where recycling rates already exceed 70% (Craven, 2015).

Against this background, the clear definition and sharing of best practice techniques is an essential approach in the development of new policy and strategic frameworks for the construction sector, contributing towards the implementation of sustainable development strategy (European Commission, 2015b). This approach underpins the sectoral reference documents developed under article 46 of the Eco-Management and Audit Scheme, EMAS, regulation (European Parliament and the Council et al., 2009). These sectoral reference documents include a description of best environmental management practices, BEMPs, underpinned by quantitative benchmarks of excellence, based on sector-specific key performance indicators, that validate high levels of environmental performance. Multi-expert-stakeholder involvement in the process of BEMP definition ensures that BEMPs target those areas with proven improvement potential and economic feasibility. The compilation of priority BEMPs for CDW prevention and management contained in the sectoral reference document for the construction sector therefore establishes a systematic framework to operationalise the circular economy paradigm for important resource flows.

This paper synthesises the main principles underpinning the definition of *best* practices for the management of CDW, reducing waste generation, minimising transport impacts, maximising re-use and recycling by improving the quality of secondary materials, optimising the environmental performance of treatment methods. The authors of this paper draw upon BEMP definition experience and insight gleaned from the development of six sectoral reference documents, and from European stakeholder inputs regarding CDW management for two relevant sectors: the building and construction sector (Joint Research Centre - European Commission, 2012) and the waste management sector (Zeschmar-Lahl et al., 2016).

2. Characteristics of construction and demolition waste (CDW)

CDW is a generic term that defines the waste generated by the economic activities involving the construction, maintenance, demolition and deconstruction of buildings and civil works. The term "site" is, usually, the most appropriate to define a production facility where CDW is generated. Actually, the distributed nature of construction and demolition *sites* is commonly characteristic of the sector in all Member States of the European Union.

The composition of CDW varies widely as a function of the type of site: e.g. road construction generates a huge amount of excavated materials that, if no further use is possible, will become waste, while a building demolition site will generate a large amount of waste concrete. The heterogeneity of construction activities therefore makes impossible to establish reliable consumption patterns of construction materials or waste generation rates per capita, per work or per m^2 floor area. In this regard, several authors have tried to establish quantitative ranges of CDW generation rates in a benchmarking exercise (Mália et al., 2013). These rates link the construction activity and the amount of waste per unit of built, demolished or refurbished area to CDW indicators for different types of structures, construction techniques and traditional practices. For instance, precast and prefabricated structures generate less construction waste, as the manufacturing process is less wasteful and designs are specific for each building. At the same time, the expected amount of CDW and its composition is substantially different if timber or reinforced concrete structures are used. Table 1 provides an overview of the range of components of CDW. Construction of new buildings generate from 18 to 33 kg per m^2 built area of waste concrete when using concrete structures, while timber-based structures generate ten times less waste. However, demolition of residential buildings can generate up to 840 kg of waste concrete per demolished m^2, while timber-based structures generate up to 300 kg per m^2. In general, concrete is the main material in CDW, if excavated materials are excluded, and is categorised under code 17 01 01 in the European List of Waste (European Commission, 2000). Other important CDW waste codes are 17 01 02 bricks, 17 01 03 tiles, 17 02 01 timber, 17 02 02 glass, 17 02 03 plastics, 17 03 02 bituminous mixtures, 17 04 07 metal mixtures, 17 06 04 insulation materials, 17 08 02 gypsum-based construction materials and 17 09 03 construction and demolition wastes (including mixed wastes) containing hazardous substances.

Table 1
Construction and Demolition Waste composition (BioIS, 2016).

Waste Category	%, min–max range
Concrete and Masonry	40–84
Concrete	12–40
Masonry	8–54
Asphalt	4–26
Others (mineral)	2–9
Wood	2–4
Metal	0.2–4
Gypsum	0.2–0.4
Plastics	0.1–2
Miscellaneous	2–36

Although the specific environmental impact (per Mg) is low if compared with other waste streams, the aggregate environmental impacts of the large quantities of CDW are significant, and derive mostly from logistics and land occupation at the waste end of the value chain (and resource consumption upstream). The impact of CDW logistics and treatments is shown in Table 2. The most relevant environmental aspects of CDW generation are influenced by design decisions at the start of the construction value chain; 'designing-out' waste is a term in use for CDW, and refers to design and planning commercially available techniques to avoid the generation of waste. The most popular designing out waste technique is the use of prefabricated modules, which is more common in modern methods of construction. With this approach, more than 80% of total construction waste can be avoided. For instance, the construction of a new residential building where the structure is prefabricated would save around 80–100 kg of waste per 100 m^2 floor area (Mália et al., 2013).

Some European countries already achieved the objective of 70% recycling for CDW. Statistics show that the total mass flow of recovered waste accounts for more than 80% of the total waste generation in Member States as the Netherlands, Germany or Denmark (Eurostat, 2017). However, in some regions there is a significant amount of illegal dumping and a heterogeneous market for secondary materials, which hinders the development of secondary materials market, that may not be reflected in official statistics. For instance, high collection rates of

Table 2
Life cycle environmental burdens for one Mg of Construction and Demolition Waste treated according to different methods (Blengini and Garbarino, 2010).

Treatment	Global warming potential, kg CO_2e/Mg	Primary Energy, MJ/Mg	Land Use*, PDF m^2 a/Mg
Collection	6	100	0.15
Landfill	15	300	0.80
Recycling	2.5	45	0.18

*Potentially Disappeared Fraction [PDF·m^2 y] of species over a certain amount of m^2 during a certain amount of year is the unit to "measure" the impacts on ecosystems. "The PDF m^2 y represents the fraction of species disappeared on 1 m^2 of earth surface during one year. For example, a product having an ecosystem quality score of 0.2 PDF m^2 y implies the loss of 20% of species on 1 m^2 of earth surface during one year." (Jolliet et al., 2003).

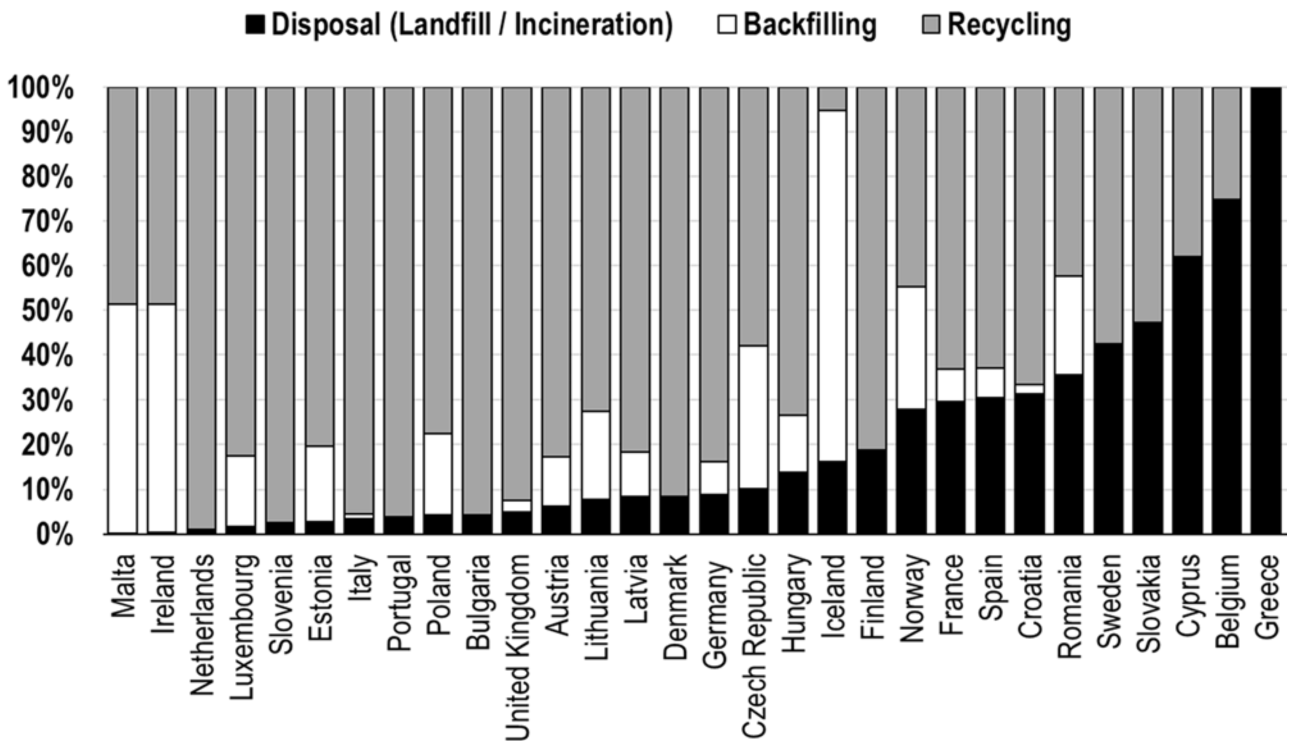

Fig. 1. Construction and Demolition Waste's Mineral fraction treatment in 2014 (Eurostat, 2017).

well-segregated CDW are achieved in Spain but the market uptake of recycled materials is really low; large storage areas at treatment plants have essentially become temporary landfills (Joint Research Centre - European Commission, 2012).

Indeed, an inherent problem of CDW management at national level is the compilation of reliable statistics to inform and monitor policy. The mineral fraction of construction waste constitutes category 12.1 of the European Regulation on waste management statistics, which basically differs from the categories defined in the European list of waste. Therefore, the success of certain policies at national level are not easy to monitor. Fig. 1 shows CDW treatments that Member States reported in the year 2014 (Eurostat, 2017). As observed, a huge amount of waste is basically sent to final disposal, mainly landfill.

Depending on the nature of the construction project, concrete waste ranges 40 to 85% of the total waste generated on site (Rimoldi, 2010). Except for some elements such as beams or blocks, which can be *dismantled* from a building, "clean" crushed concrete waste is barely reusable and its recycling produces an usually downgraded product (aggregates), as recovery of initial constituents from cement or the original aggregate is not feasible. Recycled concrete aggregates, RCA, are usable for the so-called unbound applications (e.g. road sub-base fillings) or as secondary materials in the manufacture of new concrete. Europe consumes around 2.6 billion Mg of aggregates (European Aggregates Association, 2017). If the entire quantity of CDW is transformed into recycled aggregates, only a 2% substitution of virgin aggregates would be achieved. In the UK, 6.4% of the aggregates for concrete came from secondary sources or recycled materials in 2015 (The Concrete Centre, 2016). Therefore, there are no technical barriers for a virtual 100% recycling of the main constituents of CDW, concrete and ceramic wastes, but barriers derived from their commercialisation, the market of virgin materials or their logistics. A good example of these barriers are observed in Spain, where, during 2017, 100 million Mg of aggregates were consumed in 2017 (ANEFA, 2017), but it is though to correspond to an actual 22% of the total production capacity of the sector. On the other hand, only 10 million Mg of CDW are generated, from which the current management system can generate up to 3 million Mg of usable recycled aggregate (FERCD, 2015); the impact of this secondary material in the total system would only be 3% of the total aggregates market, but competing with the highly available resource of natural aggregates.

The highest quality use of RCA is for new concrete. However, the low cost of extracted natural aggregates is a main drawback for the uptake of secondary materials in many locations in Europe, as extracted resources would have similar costs to recycled aggregates. As shown for the case of Spain, in some Member States there is a healthy market of affordable natural aggregates so the economic savings on the total cost of aggregates in the final product are insignificant. In addition, the environmental impact of natural and recycled aggregates e.g. in terms of greenhouse gases emissions is highly dependent on their transport (Blengini and Garbarino, 2010). Recycled aggregates from masonry and ceramic wastes, usually mixed with waste concrete, are less usable in bound applications, but their volume is certainly smaller and their technical viability is proven (Jiménez et al., 2013).

Several case studies around Europe demonstrated more than 95% CDW recycling, where recycling means any recovery operation by which waste materials are reprocessed into products materials or substances, as defined in the Waste Framework Directive (2008/98/EC) (Joint Research Centre - European Commission, 2012) and showed how market barriers could be overcome in relation to (i) availability, (ii) economics and (iii) acceptability. The profit margin on recycled aggregates depends on the localisation of the resource, which has to be closer than conventional quarries, and the respective taxes applied to landfill and natural aggregate extraction (European Aggregates Association, 2006). Denmark and the Netherlands have been very successful in promoting the recycling of CDW using these kind of instruments. Along with other drivers, these market-oriented regulatory tools, including taxes or levies, developed by the public administration, or environmental credits certified by relevant industry-led ecolabeling schemes such as BREEAM or LEED, contribute to improved outcomes.

Finally, a cultural misunderstanding is that recycled aggregates in concrete have much lower operational performance than natural aggregates (Adams et al., 2016). Researchers have shown that, with proper waste separation, recycled concrete aggregates can substitute 100% natural aggregates in quality applications of concrete (Adams et al., 2016; McGinnis et al., 2017; Silva et al., 2014; Wijayasundara et al., 2017).

3. Best environmental management practices for construction and demolition waste

3.1. Methodology for the identification of best environmental management practices

According to the EMAS regulation 1221/2009, a BEMP is the "most effective way to implement the environmental management system by organisations in a relevant sector and that can result in best environmental performance under given economic and technical conditions". The identification of BEMPs is a process very similar to that for best available techniques within the framework of the European Directive on Industrial Emissions, formerly Integrated Pollution Prevention and Control (Schoenberger, 2009). In a first approach, data is collected from the literature, industrial experience, and direct data and feedback from a technical working group of European experts. Performance data is used to recognise best environmental management practices, while a deeper study is required to qualify the selection of best practices regarding applicability and economic efficiency. In the case of the construction sector, a technical working group of European experts, practitioners, regulators, constructors, developers, etc was established at the beginning of the exercise. In a first meeting, the experts give recommendations and indications to the team of the Joint Research Centre of the European Commission. The received information drives research on the topic, helps organising site visits and experts are consulted. A first draft report is delivered to the technical working group, which then ratifies, modify or comment on the list of best practices, the indicators used to measure their performance and benchmarks of excellence where applicable.

The approach for the identification of BEMPs is further defined in other publications derived from EMAS sectoral reference documents, e.g. for energy efficiency, (Galvez-Martos et al., 2013), supply chain management, (Styles et al., in the retail trade sector, 2012), or water management in the hospitality sector, (Styles et al., 2015)

3.2. List of best practices

Table 3 summarises BEMPs selected for the management of CDW. Best practice definition involved consideration of the entire value chain of the construction sector, and follow a sequence along the chain. In the first instance, best practices address the definition of management strategies in a preconstruction phase (project inception and design), then techniques around prevention and collection are proposed in a second category, and re-use, treatment and material recovery practices are discussed in the third and fourth category.

Fig. 2 illustrates the integration of the identified best environmental management practices into the construction value chain, i.e. preconstruction (inception and design), construction, demolition and waste to products.

CDW best practices essentially operationalise circular economy principles within the construction and demolition sector and beyond. Most of the defined best practices in e.g. demolition are oriented to maximise the re-use of elements, facilitate recycling, material recovery and secondary uses of materials through e.g. quality assurance schemes for materials derived from waste.

This work presents those best practices with proven environmental benefits that are replicable and affordable for waste authorities and managers. Single case studies have generally been avoided where they do not have wider applicability, and some best practices are specifically oriented to drive significant environmental improvement in countries and regions with a poor performance of CDW management – these BEMPs may be considered "average" or "standard" in the context of other national frameworks outside of their intended target.

3.3. Waste management strategies

The elaboration of **CDW management plans or strategies** is a very common approach in Europe, since the elaboration of integrated waste management plans is mandatory (European Parliament and the Council, 2008). However, the quality of implementation and consequent outcomes diverge considerably; for instance, CDW management has become a privately driven activity in countries with a restricted supply of virgin materials, well-extended environmental awareness and with a reliable CDW recycling infrastructure. In general, to be effective, CDW management plans must be accompanied by regulation and enforcement practices, or economic drivers, such as taxes, levies, etc. Key elements of a best practice strategic plan at different scales are summarised in Table 4.

The impact of CDW management strategies is not easily quantifiable for two main reasons: the evolving economic framework introduces difficulty in the quantification of business as usual, BaU, performance; and the allocation of the environmental benefits between the whole strategy or to a single technique or management practice (e.g. the establishment of a levy or the investment in recycling plants).

In any case, there are examples where a whole strategy resulted in a rapid improvement from the BaU counterfactual scenario: in the UK, the establishment of sound environmental policies and strategies around CDW through the Waste Resources Action Programme, WRAP, contributed to the increase of the recycling rate up to 90% for the whole UK (DEFRA, 2017), achieving exemplar cases with 100% concrete or metal wastes from construction sites diverted from landfill, and achieving savings of more than 200 kg CO_2 per GBP 100,000 value of the construction (Institute of Carbon and Energy, 2017). In the UK, the involvement of stakeholders was articulated using the "Halving Waste to Landfill Commitment", which involved more than 750 companies from the whole supply chain of construction (Waste and Resources Action Programme, 2011).

One of the key aspects for strategic plans is the involvement of stakeholders. The International Solid Waste Association established in 2012 a range of good practice mechanisms in the always challenging involvement of stakeholders (ISWA, 2012):

- Consultation, communication and involvement of users.
- Participatory and inclusive planning: those parties showing interest should meet regularly to measure the performance of the system, define or update objectives and monitor progress against benchmarks.
- Inclusivity at all levels: the creation of local waste platforms with decision-making attributions is a particularly recommended practice.

As for any environmental policies, effective waste management strategies include a mix of complementary measures such as regulatory, economic, educational and informative instruments (OECD, 2013; van Beukering et al., 2009). In this context, **economic instruments** are designed to motivate waste producers to divert waste from landfills, recycle more waste and optimise the use of resources, so waste is (i) prevented, (ii) well managed, and (iii) optimally treated. These instruments can have greater impact than regulatory mechanisms, and introduce taxes or levies to the polluter, linking the cost of waste treatment with the actual amount of waste generated by, for example, charging per unit of waste. While these instruments have more recently been implemented for household waste streams, the construction industry and CDW managers have extensive experience on these types of instrument, including landfill taxes, aggregate levies or others. With regard to best practice, the business to business, B2B, schemes in Europe are particularly remarkable. For instance, the existence of a B2B deposit refund scheme is sometimes a common practice for highly reusable packaging, like pallets, construction packaging, drums and others (Lundesjo, 2011; Waste and Resources Action Programme,

Table 3
Summary of best environmental management practices for CDW.

Best Environmental Management Practice	Main Description (BEMP is …)	Key Actors (decision makers)	Impact of best practice on waste management cost	Relevant Stakeholders (addressed actors in the value chain)
Waste Management Strategies				
CDW management plans	To develop local regional and/or national CDW management plans that involve main stakeholders, prioritise waste prevention and re-use, establish minimum sorting and management requirements, identify and quantify amounts of CDW and treatment needs, drive innovation on recycling opportunities, and regulate or standardise the management of hazardous materials.	Public authorities at national and regional levels	Low	Contractors, waste management organisations, developers, clients, suppliers and all actors of the construction value chain.
Economic Instruments	To use economic instruments to encourage and maximise the environmental performance of waste management systems by driving cost savings to recycling (landfill tax), use of recycled materials (aggregates levy) or B2B refund systems.	Public authorities at national and regional levels, contractors, suppliers	High	Contractors, waste management organisations, developers, designers and clients.
Site Waste Management Plans	To prevent and manage waste by defining a standard or regulated site waste management plan specifying actions for every type of waste, the expected generated amount of waste, management alternatives, allocation of resources, estimate and minimise costs and define responsibilities.	Public authorities at regional and/or local levels, waste management organisations, developers, construction companies	Medium-High	Contractors, developers, clients
Prevention and Collection				
Designing out waste	To prevent and minimise waste at every stage of the life cycle of a building during the specification and design phase by identifying opportunities for the use of prefabricated elements, modern methods of construction, rental and re-use of auxiliaries and reduced use of onsite cuttings. For building demolition, this technique allows the systematic disassembly of buildings in order to maximise the re-use and recycling of recovered materials.	Designers, architects	Low	Waste management organisations, developers, clients, suppliers
Site waste management and prevention	To prevent and manage waste, including the monitoring of waste generation, the establishment of waste separation and collection strategies and the update of the site waste management plan.	Site managers	Medium	Contractors, waste management organisations, developers, clients, suppliers
Material Use Efficiency	To avoid material loss by improving the logistics of materials, planning the management of remains and applying innovative storage and handling practices.	Designers, architects, site managers	Low	Suppliers, contractors
Re-use				
Building de-construction	To evaluate and maximize the recovery of materials from buildings at their end-of-life stage, following the principles of transparency (all elements are visible), regularity (same materials are used for the same applications), and simplicity (limited number of materials and components and easy-to-separate materials).	Designers, architects, developers, contractors	High	Suppliers, waste management organisations, demolition contractors
Re-use of materials	To harvest materials or auxiliaries at construction or demolition sites, avoiding waste generation of e.g. bricks, tiles, slaps, beams, pallets, formworks, auxiliary structures, etc.	Site managers	Low-Medium	Contractor, suppliers, developers
Waste treatment and material recovery				
Waste sorting and processing addressing the acceptability of recycled aggregates	To separate and process mono-fractional waste streams, both at mobile or stationary plants, in order to maximise the production of high quality recycled aggregates.	Public administration, suppliers, waste management organisations	High	Contractors, site managers, waste management organisations, demolition contractors, standardisation bodies
Quality assurance schemes	To participate in industry-wide agreements on the quality of recycled products or quality assurance schemes in order to increase the uptake of recycled aggregates, encourage waste segregation and diversion from landfill.	Public authorities at national and regional levels, waste management organisations	High	Contractors, developers, clients
Recovery of plasterboard	To recycle waste plasterboard and other sources of waste gypsum to the manufacture of new plasterboard, according, if available, to a quality assurance scheme or industrial agreement.	Suppliers, designers, architects, developers, clients	High	Waste management organisations, demolition contractors

Fig. 2. Best environmental management practices for CDW management in the construction value chain.

Table 4
Common elements of a best practice strategic plan at national, regional and local (municipal or county) scale.

National plan	Regional plan	Local plans
• Identifies and quantifies CDW management opportunities • Involves stakeholders from the construction industry • Defines CDW management targets and environmental policies • Prioritises waste prevention • Provides a realistic regulatory framework for the industry, including codes of practice	• Implements national policies • Quantifies the needs for collection, treatment and recycled material demands • Establishes investment plans for treatment facilities, research and development needs • Provides or helps in the development of tools for the industry for the safe recycling of materials (e.g. quality assurance schemes) • Defines a performance baseline on past quantifiable information • Identifies future flows of waste	• Involves local industry and contractors • Prioritises waste prevention in local construction projects by establishing environmentally-friendly public procurement policies • Establishes buildings re-use schemes • Establishes minimum waste sorting requirements • Aims to clear guidance for small waste producers and SMEs • Establishes enforcement, communication mechanisms, economic instruments and municipal collection points to avoid poor sorting, low collection rates and illegal dumping.

2008a), and these practices have dramatically reduced the amount of waste generated at construction sites. Although waste managers are not involved in this particular approach, they are key in the management of the necessary reverse logistics, e.g. in construction consolidation centres.

At the local level, some municipalities have applied **traceability** requirements for CDW in their local licensing. For example, municipalities in Spain are charging a deposit on the estimated amount of wastes reported in the site waste management plan as part of the essential licensing requirement. The deposit is re-paid to the contractor when "waste management certificates" are submitted to the authority. This particular deposit-refund scheme, managed by municipalities, has potential to become a BEMP, but its current implementation does not meet BEMP requirements for the following reasons:

- It is oriented to avoid illegal dumping, i.e. it does not increase the performance of the system but avoids a particular local problem of CDW management.
- Legally, municipalities do not need to issue permits for their own construction sites. The waste management deposit becomes, then, voluntary for contractors working with the municipality.
- The lack of enforcement affects the performance of the scheme. While large construction companies and contractors were already applying BEMP without the need for the deposit, small producers are still failing to fulfil this practice.

During the construction activity, **site waste management plans, SWMP**, have been proven as an effective measure for the actors involved in a construction or demolition site to improve the performance of CDW management. The elaboration of SWMPs is a legal requirement in some European countries, but not in all, and therefore may still be considered a BEMP. Best practice SWMP go beyond legal requirements by fitting into an overall ambitious strategy, where two main phases are identified (Joint Research Centre - European Commission, 2012):

- SWMP design. In this phase, the scope of the plan is developed, by e.g. identifying materials to be recovered, re-used, recycled and disposed during construction or demolition. Waste management responsibilities are defined, and the instruments for monitoring, collecting and promoting correct waste management practices are identified, along with measurable indicators and targets. During the plan design phase, waste types will be defined, estimated, and the waste management technologies will be sized. A first cost estimation will be produced and potential savings will be identified. Procedures for removal, separation, storage, transportation and any waste handling will be developed. A communication strategy should also be defined in a best practice SWMP. During this phase, waste prevention techniques, re-use and recycling opportunities will be identified per waste stream and their potential on-site application will be evaluated.
- SWMP implementation. Once the main procedures and strategies are defined, the waste manager responsible for the site should communicate and explain the plan to all the relevant actors within the site and external stakeholders affected by the site activity. The areas for waste storage and the available resources should be well

Table 5
Waste prevention opportunities in the design phase.

Origin of waste	Opportunity to reduce waste through design
Demolition	Re-use existing structure and facilitate maximum recovery rate during deconstruction.
Materials available at site	Re-use, recycle and setting out recycling/re-use targets.
Temporary sites	Choice of appropriate construction method.
Excavated material	Correct foundation depths and earthworks to get a zero cut.
Design changes	Design must be flexible and adaptive, although last minute changes should be avoided to reduce the amount of material losses.
Design inception	Use environmental criteria to define targets on the performance of the building regarding waste.
Design decisions	Use prefabricated elements and standardised design to avoid off-cuts.
Off-cuts	Simplify building form to reduce site cutting and use manufacturer dimensions for specific elements.
Over – ordering	Produce good estimates of materials requirements. Revise periodically estimation methodology.
Damaged materials	Minimize the need for stockholding, e.g. by choosing materials with just-in-time delivery.

identified within the site, and waste containers should be placed as close as possible to the generation point. Training and promotion of the plan should be regularly performed, especially with new contractors or subcontractors, and a documentation file shall be kept updated.

3.4. Prevention and collection

In the building life cycle, wastes are generated from demolition material (of the previous construction on site), damage of materials, off-cuts, design changes, temporary works materials, contamination of clean materials, packaging, etc. Excavated materials and soils may be considered also as wastes if they are polluted or if for administrative reasons they need to be managed as wastes. Approximately 33% of waste generation on a typical construction site can be attributed to designers failing to implement waste prevention measures during the design phase (Osmani et al., 2008), while the remainder can be considered unavoidable with current practices and techniques. Table 5 shows some opportunities for *waste prevention during design*, i.e. **designing out waste** (adapted from Waste and Resources Action Programme, 2012).

Modern methods of construction have a huge impact on waste generation during construction, since off-cuts and concrete handling are avoided. The waste reduction potential is up to 90% for techniques such as:

- Volumetric building systems: Off-site manufacturing of three-dimensional modules, e.g. roof and external insulation, roof tiling, brick and block work, etc.
- Substitution of concrete frame: timber.
- Pre-cast panels: panelised building systems for staircases, roofing, basements, etc.
- Steel frames: substitutes concrete and eliminates waste generation.
- Structural insulated panels and prefabricated roof systems.
- Composite panels.
- Pre-cast cladding.
- Light steel frame for building façades.
- Structural pre-cast elements.
- Insulating concrete formwork.

An example of the application of modern methods of construction is the Middlehaven Hotel in the UK (Waste and Resources Action Programme, 2008b), where a series of precast elements, volumetric pods, pre-cast columns and foundations were able to avoid 75% of the total waste expected from traditional construction methods, saving more than half a million EUR from waste disposal and unnecessary construction materials. However, the environmental performance of a specific application should use LCA to evaluate the actual environmental performance.

On-site **waste prevention and collection** are techniques that should have been identified, designed and scoped in a general construction site management protocol, which may be articulated in a specific SWMP. From the endless list of waste management options at construction and demolition sites, four main activities of the waste management activity are identified:

- **Estimation of waste generation and provision of resources**. Best segregation options for a construction site should be analysed in advance of the construction activity, so resources can be allocated for waste management. The estimation of wastes generated during the construction activity should be based on a tailor-made estimation (Martínez-Bertrand and Tomé, 2009), which should be optimised with the help of the previous experience of the contractor.
- **Collection and segregation techniques**. Several collection techniques are needed to help site labourers to perform correctly. Identified standard practices have the following common basis: (i) waste collection bins are identified for each type of waste; the size of each bin or container is appropriate taking into account the estimated amount to be generated, the number of containers and the foreseen number of waste deliveries; (ii) waste collection bins are usually placed at the same point of the site (e.g. labelled as 'eco-point', 'recycling point', etc.); (iii) temporary collection points are usually placed next to a work position in order to increase the efficiency of waste segregation, but which usually depends on the characteristics of the position; (iv) hazardous wastes are collected in a separated point, protected from wind, rain and over a sealed surface with the appropriate measures to prevent and minimise pollution of rainfall water; (v) all labourers, independently if they come from the main contractor or a subcontractor are aware of the on-site waste management techniques, (vi) there is enough space available for waste deliveries by truck; and (vii) waste collection points are identified in a site plan and the plan is made available to all relevant actors.
- **Procedures and methodologies to ensure best management options**. These techniques usually refer to on-site control techniques, such as visual inspection, computerised or photographic register, signs, symbols and information, issuing and control of waste management certificates, and, in case it is required, pre-treatment of waste is available on-site when high segregation rates need to be achieved, e.g. compactors, roll packers, cardboard balers, shredders for wood, or portable crushers.
- **Provision of waste logistics.** Usually, two on-site collection methods are observed: reactive and scheduled. For large fractions, such as inert fractions of CDW, a reactive collection is required, e.g. a full skip is substituted by another empty skip on demand. For smaller volumes of wastes of constant generation, such as those similar to municipal solid wastes, scheduled collection is the best option.

Best management practices on **material use** refer to logistics schemes that optimise material use by minimising the amount of raw materials stored on site, which reduces the likelihood for supplied

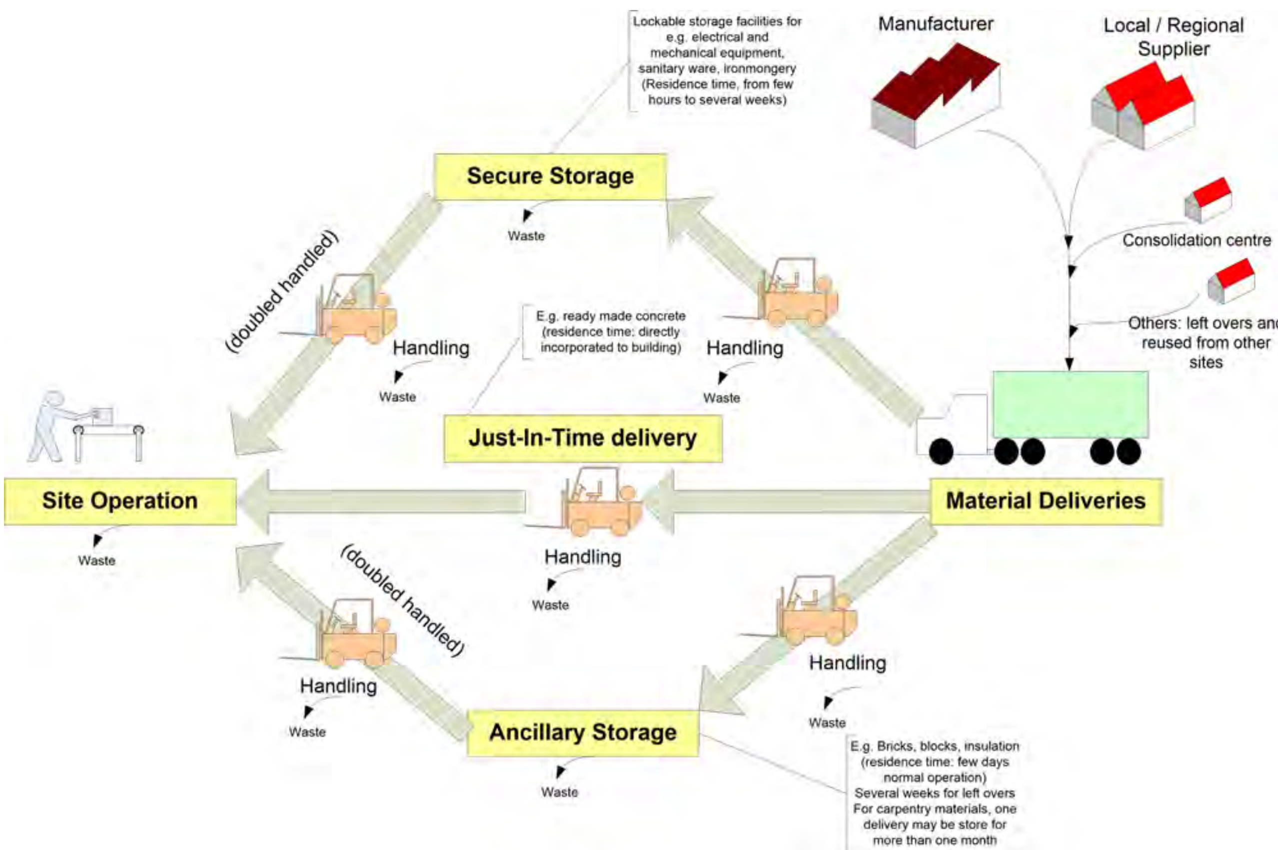

Fig. 3. Supply logistics options to construction sites. Source: (Joint Research Centre - European Commission, 2012).

materials to become waste. In traditional logistics, the majority of materials are stocked when they arrive on a construction site. This means that materials are double handled, increasing the risk of damage and the rate of waste generation along with the subsequent cost. In this sense, *stockholding* is a term defined as the process of holding materials in readiness for subsequent activities (Constructing Excellence, 2006). Material use efficiency can avoid environmental impacts because: less fuel is consumed if less material is transported, less materials leftovers are produced if stockholding is reduced down to a minimum, etc.

Fig. 3 shows an overview of logistics techniques at construction sites. Whenever supply is made by manufacturers (e.g. for specially designed construction elements or products), by local or regional suppliers, by urban consolidation centres or by the same construction company, three main practices are observed: *ancillary storage, secure storage* and *just-in-time delivery*. Ancillary storage (e.g. for bricks, blocks, timber, etc) is used to buffer the supply of materials for the smooth operation of sites. Secure storage has a similar function, but a higher degree of security has to be ensured for materials of high value (metals, kitchens, sanitary ware, etc.). The third technique is just-in-time delivery and constitutes the preferred technique for the supply of ready-mix concrete and other bulky materials. In the case of construction sites in the centre of large cities, storage typically has to be kept to a minimum due to lack of space. In these cases, delivery is normally just-in-time, while buffering is performed through consolidation centres for best performance.

3.5. Re-use of materials

From the circular economy point of view, the best re-use option in the construction sector is the re-use of the entire building. Factors such as space, integrity, aesthetics, refurbishment costs and client satisfaction play a key role on the feasibility assessment of the potential of building re-use (Institute of Civil Engineers, 2008). In many cases, the most economic option will be the demolition of buildings, which, as traditionally conceived, produces large amounts of demolition waste that often results in a significant portion of the total waste stream. **Selective building deconstruction** is an alternative to demolition that involves a systematic disassembly with the objective of maximising re-use, recycling and diversion from landfill.

Although selective deconstruction is able to separate different types of materials at source, it is not a preferred practice due to the poor economics of dismantling; the actual effort, if measured in time, skills and labour, is significantly higher than for conventional demolition (Joint Research Centre - European Commission, 2012). Those achieving best performances tend to strategies between conventional demolishing and full component-by-component dismantling. The application of selective deconstruction techniques usually involves the following steps:

- First, a hazardous substances audit and an evaluation of the need for specialised stripping, e.g. of asbestos, should be performed.
- Second, manual dismantling of re-usable parts is the preferred option for directly re-usable parts, as glass, precious wood, sanitary ware, heating boilers, re-usable radiators, etc.
- Once the building is empty of directly re-usable elements, floor coverings, ceilings and combustible and non-combustible waste should be stripped and segregated.
- Finally, depending on the type of building, wooden beams, steel frames can be re-used, while buildings with concrete are usually demolished and concrete waste crushed to produce aggregates.

This selective dismantling of buildings has several advantages over conventional demolition; it increases the diversion rate of CDW from landfills towards more sustainable direct re-use of building components and recycling of materials. Time and resource allocation are usually the main drawbacks of a deconstruction process. However, adaptive planning of the deconstruction works can also lead to considerable reductions of deconstruction duration.

Re-use, as a best practice for CDW management, refers to all harvested materials, construction elements and building components that can be used in a specific site, such us:

- Harvested construction products and building elements, e.g. bricks, tiles, concrete slabs, beams, wood frames, etc.
- Re-usable auxiliary materials, such as wood from formworks, pallets, auxiliary structures. The re-use of these is a very common practice in the construction sector and has a non-negligible impact on the economic performance of construction contractors.

The re-use of building components and construction products has a significant effect on the overall life cycle environmental performance of the construction activity. Approximately 40% of embodied energy can be saved, despite an increase in transportation needs, and more than 60% of the carbon footprint of the concrete structure can be saved when re-using prefabricated slabs (Roth and Eklund, 2003).

3.6. Waste treatment and material recovery

Current **CDW processing and recycling techniques** can be considered well established and their implementation is common across Europe. However, the nature of the final secondary materials and the market penetration differ widely. A common CDW recycling plant usually consists of (1) reception, weighing and visual inspection, (2) manual preselection (for unsegregated streams), rejection and diversion to alternative treatments, (3) screening of large materials, (4) magnetic separation, (5) manual separation of plastic, wood and other waste streams if required, (6) crushing, and (7) screening and secondary crushing, which is applied depending on the goal product mix.

A CDW treatment plant will normally produce aggregates from the inert fraction of CDW, while other types of wastes or recovered materials (metals, plastic, wood, and MSW-like in some cases) are diverted to the appropriate treatments. From well sorted waste, high quality aggregates can be produced, since clean crushed concrete aggregates have a much higher applicability than mixed crushed masonry-concrete aggregates. As an example, the standard classification of recycled aggregates (RA) in Germany is made through a DIN standard 4226-100 (Table 6).

The final destination of RA is the substitution of virgin materials. Although main substitution rates are achieved in low grade applications, as base, or sub-base materials for roads and backfilling, higher grade applications, e.g. aggregate for new structural and non-structural aggregate, have a high potential. Although some generalisations can be made, as shown in Table 7, caution is always required in the application of standards in the construction industry, as they are usually applied at national level (Pellegrino and Faleschini, 2016). Upcycling is possible, but applicability is quite low: e.g. crushed concrete sand can be used in cement production, but with a very low substitution rate of the raw meals (around 2%) due to composition limitations (Hauer and Klein, 2007).

Table 6
Classification of aggregates according to German DIN 4226-100.

DIN Classification	Type 1	Type 2	Type 3	Type 4
Name of recycled aggregate (RA)	Concrete and crusher sand	Mixed wastes plus crusher sand	Masonry plus crusher sand	Mixed plus crusher sand
Concrete and natural aggregates	≥90%	≥70%	≤20%	≥80%
Clinker, non-pored bricks	≤10%	≤30%	≥80%	
Sand-lime bricks			≤5%	
Other mineral materials	≤2%	≤30%	≤5%	≤20%
Asphalt	≤1%	≤1%	≤1%	
Foreign substances	≤0.2%	≤0.5%	≤0.5%	≤1%
Density, kg/m^3	≥2000	≥2000	≥1800	≥1500

(Pellegrino and Faleschini, 2016).

The benefits from CDW recycling as aggregates cannot be generalised without a large number of assumptions. Studies have considered different scopes and produced varied results owing to different assumptions or framework conditions. The following conclusions (Hiete, 2013) regarding the environmental performance of crushed concrete recycling have been made:

- Site characteristics are critical: the location influences transport distances while composition influences the nature of recycled materials and determines the final application.
- During the use phase, there is no fixed standard for the leachability of recycled aggregates.
- When balancing benefits from primary aggregate substitution, the type of application and the type and origin of the natural aggregate strongly influences the life cycle performance.
- However, washing, which is applied when site segregation is poor, can count more than 99% of the total environmental impact (Korre and Durucan, 2009).
- Although there are studies confirming the better environmental performance of the recycled aggregates supply chain, the production and crushing of concrete is more energy intensive than for primary aggregates, and the environmental impact can be compensated if the ratio of transport distances for primary aggregates versus recycled aggregates is above four (Chowdhury et al., 2010).

The use of RA and RCA helps to reduce the use of virgin materials from quarries, which usually have a high environmental impact at local level. For example, the German regions of Berlin and Baden-Württemberg achieve recycling rates higher than 90% for CDW, which can be attributed to the existence of proper standards and environment regulations (APPRICOD (Assessing the Potential of Plastics Recycling in the Construction and Demolition Activities), 2006; QRB, 2009). From the life cycle perspective, the use of recycled aggregates produces a net reduction in the CO_2 emissions and primary energy consumption, since the extraction of virgin materials is avoided, but some trade-offs must be taken into account. For instance, regarding the health and safety issue in recycling plants, at least 20–25% of dust in the surroundings of recycling plants has been detected to be of a diameter of less than 10 μm (Kummer et al., 2010) and, therefore, its release should be duly controlled, e.g through the implementation of de-dusting devices in screening, crushing and handling operations. Also, the location of recycling plants close to urban areas, although good in terms of life cycle environmental impact, has an adverse effect due to noise, vibration and emissions from the commonly used diesel engines.

The recycling of CDW from building construction or demolition introduces the risk of potentially **hazardous materials** that are contained in the original waste material. For instance, concrete foundations from the 1960's contain hazardous PCB substances, which are considered to be very harmful, e.g. as carcinogens. Other materials, such as solvents in paints, tar-based emulsions from roads, asbestos, etc., are controlled, although the national approaches differ; a current best practice example of PCB from construction management can be found in Denmark (Butera et al., 2014; Zeschmar-Lahl et al., 2016).

In order to achieve a less heterogeneous management landscape on the management of hazardous CDW in Europe, the European Commission mandated CEN for harmonisation on the assessment of dangerous substances. As a response, a new Technical Committee – CEN/TC 351 – was created: 'Construction products: assessment of release of dangerous substances'. This committee will provide tools and assessment methods for the quantification of dangerous substances, which may be released from construction products to the environment

Table 7
Possibilities for recycled construction materials.

Material	Use	Applicability	Specifications/restrictions for RA and RCA
RCA: Recycled Concrete Aggregates (usually with a minimum of 90% concrete content)	Earthworks, filling and road sub-bases	RCA and RA are usually applicable to this use. There may be restrictions on the physical properties because of sulphate content (causing expansion and fragility) and water absorption. Usually, European Member States ask for the same technical properties as for natural aggregates, plus some standards, mandatory or optional, on concrete and impurities.	Specific requirements for recycled aggregates in terms of strength (e.g. with Los Angeles test, or with the amount of small slaps or flagstone).
	Buildings and other civil works, for structural concrete	Coarse recycled aggregates may be applied for structural concrete (mass concrete or reinforced concrete) but water demand would be higher and may cause higher cement consumption for the same resistance as with natural aggregates. Compression resistance may be reduced (as a function of quality) and elasticity is lower.	Recommendation of a 20% maximum substitution of natural coarse aggregates. Additional requirements are specified for recycled aggregates in order to keep structural properties. Dutch national standards allow for a replacement of 20% of natural primary aggregates by mixed or concrete aggregates (without additional performance tests).
	Buildings and other civil works, for non-structural concrete		Up to 100% of application if technical and environmental specifications are fulfilled.
	Buildings and other civil works, for mortar	Fines and small particles may be used to produce mortar.	Water demand is increased. A maximum of 25% of recycled mortar is recommended in order to keep properties.
	Buildings and other civil works, for cement	Fines from concrete sand crusher have similar properties to cement with natural sand.	The use of crushed cement as substitute material was first tried in Japan and a cost reduction is proven. Energy consumption reduction and saving of natural materials are the main benefits, but the chemistry of the mixture does not allow using a substitution rate more than 10%.
RA, recycled aggregates, from mixed wastes (usually with a minimum of 50% concrete content)	Earthworks, filling and road sub-bases	Applicable if the content of gypsum is low. Main application of RA is as backfilling material. Usually, not suitable for road pavement bases.	Cleaning (water washing) is required and increases costs. Same specifications as for other materials apply. Workability may be worse, as water absorption is higher and slower than for natural aggregates.
	Buildings and other civil works, for non structural concrete	Adequate consistence and resistance properties are achievable for in-situ concrete for non structural concrete. Not usable for prefabricated concrete elements.	The low density of these aggregates may be optimal for the production of light concrete. Nevertheless, durability is lower than for other aggregates.

into the soil, ground water, surface water and indoor air (Ilvonen, 2013). In this respect, an important aspect of the hazardous potential of CDW is the leachability of chemicals from produced RA. It is common that RA coming from ashes, slags and other wastes are well regulated regarding their composition, while for recycled concrete some countries apply a set of different criteria. For instance, the Netherlands does not apply a waste regulation to RA, but a common regulation is used for natural or RA in terms of environmental criteria.

Quality assurance schemes have become a key element for the marketing of secondary materials produced from CDW recycling. The construction industry, in general, has a very conservative approach to innovation, which is basically due to its traditional behaviour and the legal liability of architects, engineers, developers and contractors regarding their final products (Zeschmar-Lahl et al., 2016), so construction stakeholders rely on sound standards to support advances. On the other hand, RAs have usually had a low- grade application, e.g. as backfilling material for quarries, some sub-base applications for road and cover for landfills. But, it is well known that certain qualities of RA or RCA fit higher grade applications, e.g. as aggregate material in concrete for structural and non-structural applications. A quality assurance scheme, in this context, would establish common rules for producers and, very importantly, would increase the confidence of final users. A best practice quality assurance scheme is one that drives increased uptake of RAs and RCAs, following a voluntary agreement approach, rather than regulation, including all stakeholders along the construction value chain. Among many measures, it should include waste segregation and diversion from landfill, while defining environment-related criteria, e.g. as leaching characteristics and reference standards, and awarding, if possible, an End-of-Waste or by-product character to the secondary material produced. For instance, based on well-defined protocols and procedures, the region of Baden-Württemberg in Germany classifies three quality levels for RAs based on their leaching characteristics, and defines suitable applications for each classification (QRB, 2009). Delgado et al., 2009, collected information from some frontrunner quality assurance schemes in Europe, such as the Austrian construction materials recycling association, the region of Flanders, the SFS standard 5884 in Finland, or the programme Aggregain in the UK, established by WRAP. Although it is out of the scope of this paper to discuss the suitability of environmental performance standards, the lack of harmonisation in Europe regarding RA is remarkable and problematic. It was noted that current requirements in many Member States of the European Union are less restrictive for virgin materials than for those secondary materials consisting on RA (Saveyn et al., 2014). Regarding the performance of RA, the most important standard is the European EN 12,620 under approval (CEN (European Committee for Standardization), 2013), which specifies the properties of aggregates regardless of the origin. This standard is an attempt to standardise, under the current construction products regulation (European Parliament and the Council, 2011) a harmonised set of quality requirements. Other standards are applicable for roads (EN 13,242) or asphalts (EN 13,043).

A key exemplary case of the circular economy in action is the **recycling of plasterboard.** Plasterboard (also known as drywall, gypsum board, wallboard, etc.) consists of kiln dried panels made of gypsum plaster (rehydrated calcium sulphate dihydrate) pressed between two thick sheets of paper. In Europe, 2.35 million Mg of waste plasterboard per year from construction and demolition projects are produced and an extra 0.6 million Mg are produced during its manufacturing and installation (Marlet, 2017). However, almost all the waste plasterboard can be successfully fed into the manufacture of new plasterboard or as raw material for other uses, and plasterboard itself can incorporate wastes from other industrial processes, such as calcium sulfate from flue gas desulfurization. Plasterboard produced with 89% recycled material (mainly flue gas desulfurization wastes) was achieved by Knauf in 2013 (Knauf et al., 2013).

The importance of plasterboard segregation and its impact on the

Table 8
Applicability, economics and achievable environmental benefits of the best environmental management practice for construction and demolition waste.

Best Environmental Management Practice	Applicability	Economics	Achievable environmental benefit
CDW management plans	Well extended instrument in large municipalities or counties. The size of the municipality and the region can have a large impact on the commitment of resources and the operability of waste platforms.	Requires enforcement by public administration and the development of awareness instruments.	Diversion of CDW to landfill. Exemplary case in the UK.
Economic Instruments	The regulatory framework and its enforcement are the main barriers for the application of some economic instruments. The existence of an appropriate environmental awareness, good management skills and innovative-driven behaviour along with some good accounting practices are pre-requisites for the implementation of economic instruments, which are complex to manage from the technical, managerial and social perspectives.	The application of new economic instruments applying new fees, levies, etc., should be designed for the system to be self-sustained.	
Site Waste Management Plans (SWMP)	Well extended instrument and mandatory in some European countries. Since the plan should take into consideration the specific circumstances of the site, no specific issue on applicability is expected.	Economic benefits from SWMP implementation are not easily quantified, since its performance depends on other best practices implementation. As a rule, SWMP development and implementation costs are lower than 0.1% of total project value.	Up to 95% waste sent to recycling achievable.
Designing out waste	A modern method of construction requires of manufacturing facilities and sites with sufficient capacity for some specific elements. The extended use of traditional construction methods, design trends, availability of space, availability of skilled workers, and the regional market are the main elements conditioning the applicability of designing out waste practices.	Economics are usually favourable, since cost savings from both materials supply and waste disposal are achieved. Faster construction also makes this a competitive technique. Cost savings range from 0.1 to 1% of total project value.	Up to 75% waste reduction achieved.
Site waste management and prevention	Low material recovery rates in some countries do not necessarily mean poor management, but also a sign of lack of enforcement, lack of facilities and/or low accessibility to waste management services. (BioIS, 2016)	In general, waste management costs in construction projects are not more than 3% of total costs; therefore, costs savings through waste prevention can only achieve a small saving on-site.	Exemplary cases with up to 99% of waste diverted from landfill.
Material Use Efficiency	Space availability and the existence of nearby consolidation centres are a key aspect of stockholding of materials at construction sites. (Transport and Travel Research, 2010)	Consolidation centres or just-in-time deliveries allow a better organisation of the site, reduce waste and increase site productivity, so savings are usually achieved. Consolidation centres account for less vehicle runs than just-in-time deliveries.	The use of consolidation centres has reduced largely the amount of wastes derived from the handling of stock. Examples for plasterboard have shown materials savings of up to 15%.
Building de-construction	Building deconstruction is applicable in situations where waste management is expensive and some materials or components may be scarce, so there would be an economic drive. In most cases, skilled laboured is required, while an appropriate legal framework is in place.	The high demand for manual labour, time and very specialised light machinery makes deconstruction a rather expensive solution. Total management costs average 10–15 EUR per m^3 of CDW.	Recovery rates of up to 95–99% can easily be achieved when building selective deconstruction and dismantling are applied.
Re-use of materials	The lack of a sound market for reclaimed products and the availability of a large stock of these is a main barrier on the applicability of such materials.	Re-use of auxiliaries is a fully applied measure due to the full economic sense of such approach. However, use of reclaimed materials as a conventional source of products in construction is still way off. For instance, cost of reclaimed bricks can be 100% more expensive than conventional ones, but reclaimed steel frames can save up to 50% of investment costs.	A virtual zero waste amount sent to landfill is achievable if re-use is integrated with other best practices.
Waste sorting and processing addressing the acceptability of recycled aggregates	This technology is well spread around Europe and common for waste treatment facilities. It requires a good framework of waste segregation and a healthy demand of recycled products that avoids the accumulation of secondary materials.	Recycled materials have usually a lower cost than natural materials. In some European Member States, the cost of virgin materials is quite competitive with secondary materials due to availability and market conditions	Higher confidence from the industry, higher recycling rates (higher than 90% for some frontrunners) and significant environmental benefits from the life-cycle perspective.
Quality assurance schemes	Quality schemes and quality standards are in general adaptive to the general circumstances of the stakeholders involved in the scheme. The general recommendation is to avoid any generalisation and make a case-by-case study on the applicability of a recycled product.	Cost of RA under quality assurance schemes is around EUR 3–EUR 12 per Mg in many European locations, so they are considered to be competitive with virgin materials.	
Recovery of plasterboard	Given the chemistry of plasterboard, a maximum of 25% of recycled plasterboard can be incorporated into new plasterboard, but 100% of the raw materials could come from alternative sources, as flue gas desulphurisation by-products.	The cost of segregated plasterboard collection increases waste management costs in construction sites, but is usually compensated by gate fees for wastes with no plasterboard segregated and the revenues from low-sulphate CDW recycling.	The environmental benefit from direct recycling of plasterboard is not high (e.g. 6% less carbon footprint), but there are gains from its segregation in the management of CDW, since it reduces considerably the amount of sulphate in other fractions of CDW.

whole CDW reprocessing is of high relevance. A separate thematic area was set up by WRAP in the UK, where several local authorities introduced waste plasterboard collection at their Household Waste Collection centres, e.g. Sheffield (Waste and Resources Action Programme, 2009). Also, at European level, the project GypsumTo-Gypsum (Marlet, 2017) aimed to integrate better the supply chain of gypsum-based products by closing the loop and to increase the quantity of gypsum-based waste being diverted from landfill for recycling. Europe demands around 15 million Mg of plasterboard, and the annual production of its waste is around 2.35 million Mg. So, therefore, there is more than enough capacity for recycling.

From the whole value chain of the construction sector, several best practices have an impact on plasterboard products:

- Plasterboard panels are subject of designing-out waste practices, since proper sizing and just-in-time practices would reduce the amount of wasted plasterboard considerably.
- Plasterboard is a durable product, so panels and tiles made of plasterboard, with no damage, can easily be reinstalled (re-used).
- The product itself can incorporate secondary material up to virtually 100% of the raw material, although the industry tends to use natural gypsum. E.g. in Germany the demand for the construction material gypsum is mainly fulfilled (currently at least 60%) by gypsum as a side product of the flue gas desulphurization in the electricity production process at coal power plants.
- Reprocessing waste plasterboard can produce gypsum of high quality, according to certain standards, with a variety of potential uses apart from new plasterboard: raw material for cement manufacture, roads sub-base, and soil improvement for agriculture. The characteristics of each secondary product are defined in quality assurance schemes e.g. for the UK. In general, the presence of fibres in the waste limits its applicability to a 25% of the total raw meal for new plasterboard.
- Waste plasterboard segregation benefits other CDW recycling, as sulphates, generally coming from plasterboard, are mixed with other CDW fractions in unsorted waste management, which prevents the application of the recycled aggregate.

3.7. Applicability, economics, and achievable environmental benefit

During the research activity, all the BEMPs on CDW management have been qualified in terms of achievable environmental benefits, conditions for applicability, costs and economics of implementation, operational data, reference organisations in Europe and cross-media effects (Joint Research Centre - European Commission, 2012; Zeschmar-Lahl et al., 2016). Table 8 summarises the most important information regarding the applicability, economics and environmental performance for each of the best practice described in the previous sections.

4. Final remarks

Observations made during the exercise showed clearly an obvious heterogeneity among European Member States, especially in two areas: treatment of waste and development of markets for secondary materials. It is obvious that the technology and the potential for high performing waste management systems is already in the market and available to those regions, municipalities, waste authorities or waste contractors willing to improve their performance. However, the construction sector shows a traditional behaviour, which heavily relies on standards, while being completely economically driven. In addition, the high variety of actors involved in the CDW value chain creates a complex mesh of responsibilities, with very different decision-making chains across European Member States. Of course, the low impact of any waste-related decisions on construction project budgets does not encourage improvement beyond current standard practices. Therefore, most of the observed efforts focus on the creation of drivers addressing the whole landscape of construction stakeholders across the construction value chain. Systematic documentation of current best practices observed across Europe provides an evidence base to develop policies and management strategies that deliver circular economy solutions to the construction sector.

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