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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.

Keywords

Construction and demolition waste, circular economy, recycling, re-use, best practices, environmental management, waste management, waste logistics, recycled aggregates, plasterboard

Abbreviations

BaU	Business-as-usual
BEMP	Best Environmental Management Practice
CEN	<i>Comité Européen de Normalisation</i>
CO ₂ e	Equivalent CO ₂ emissions
CDW	Construction and Demolition Waste
EMAS	Eco-Management and 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

37 1. Introduction

38 Currently, the European construction sector produces 820 million tonnes (megagram, Mg, or 1,000 kg) of
39 construction and demolition waste (CDW) every year, which is around 46% of the total amount of total waste
40 generated according to Eurostat (Eurostat, 2017). The average composition of CDW shows that up to 85% of the
41 waste is concrete, ceramics and masonry, although CDW can be heterogeneous depending on the origin, and may
42 contain large amounts of wood and plasterboard (Monier et al., 2011; U.S. Environmental Protection Agency, 1998).
43 In any case, CDW inorganic fraction is frequently characterised as “inert” due to lack of chemical reactivity at
44 ambient conditions. Most CDW consists of excavated materials, which are considered to have a low environmental
45 impact upon disposal. If excavated materials are excluded, around 300 million Mg of CDW were generated in 2014
46 at European construction sites (i.e. EU 28 new construction, demolition or refurbishment activities).

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

61 Novel solutions, instruments and approaches are required for the management of CDW. While a recycling rate of
62 70% for non-hazardous construction and demolition waste can be considered an ambitious target in certain countries,
63 the industry has noticed that national circumstances are heterogeneous across European Member States and that such
64 a target lacks incentive for the industry of those countries or regions where recycling rates already exceed 70%
65 (Craven, 2015).

66 Against this background, the clear definition and sharing of best practice techniques is an essential approach in the
67 development of new policy and strategic frameworks for the construction sector, contributing towards the
68 implementation of sustainable development strategy (European Commission, 2015b). This approach underpins the
69 sectoral reference documents developed under article 46 of the Eco-Management and Audit Scheme, EMAS,
70 regulation (European Parliament and the Council, 2009). These sectoral reference documents include a description
71 of best environmental management practices, BEMPs, underpinned by quantitative benchmarks of excellence, based
72 on sector-specific key performance indicators, that validate high levels of environmental performance. Multi-expert-
73 stakeholder involvement in the process of BEMP definition ensures that BEMPs target those areas with proven

74 improvement potential and economic feasibility. The compilation of priority BEMPs for CDW prevention and
75 management contained in the sectoral reference document for the construction sector therefore establishes a
76 systematic framework to operationalise the circular economy paradigm for important resource flows.

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

84 **2. Characteristics of Construction and Demolition Waste (CDW)**

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

89 The composition of CDW varies widely as a function of the type of site: e.g. road construction generates a huge
90 amount of excavated materials that, if no further use is possible, will become waste, while a building demolition site
91 will generate a large amount of waste concrete. The heterogeneity of construction activities therefore makes
92 impossible to establish reliable consumption patterns of construction materials or waste generation rates per capita,
93 per work or per m² floor area. In this regard, several authors have tried to establish quantitative ranges of CDW
94 generation rates in a benchmarking exercise (Mália et al., 2013). These rates link the construction activity and the
95 amount of waste per unit of built, demolished or refurbished area to CDW indicators for different types of structures,
96 construction techniques and traditional practices. For instance, precast and prefabricated structures generate less
97 construction waste, as the manufacturing process is less wasteful and designs are specific for each building. At the
98 same time, the expected amount of CDW and its composition is substantially different if timber or reinforced concrete
99 structures are used. Table 1 provides an overview of the range of components of CDW. Construction of new buildings
100 generate from 18 to 33 kg per m² built area of waste concrete when using concrete structures, while timber-based
101 structures generate ten times less waste. However, demolition of residential buildings can generate up to 840 kg of
102 waste concrete per demolished m², while timber-based structures generate up to 300 kg per m². In general, concrete
103 is the main material in CDW, if excavated materials are excluded, and is categorised under code 17 01 01 in the
104 European List of Waste (European Commission, 2000). Other important CDW waste codes are 17 01 02 bricks, 17
105 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,
106 17 06 04 insulation materials, 17 08 02 gypsum-based construction materials and 17 09 03 construction and
107 demolition wastes (including mixed wastes) containing hazardous substances.

108

109

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

111 Although the specific environmental impact (per Mg) is low if compared with other waste streams, the aggregate
112 environmental impacts of the large quantities of CDW are significant, and derive mostly from logistics and land
113 occupation at the waste end of the value chain (and resource consumption upstream). The impact of CDW logistics
114 and treatments is shown in Table 2. The most relevant environmental aspects of CDW generation are influenced by
115 design decisions at the start of the construction value chain; ‘designing-out’ waste is a term in use for CDW, and
116 refers to design and planning commercially available techniques to avoid the generation of waste. The most popular
117 designing out waste technique is the use of prefabricated modules, which is more common in modern methods of
118 construction. With this approach, more than 80% of total construction waste can be avoided. For instance, the
119 construction of a new residential building where the structure is prefabricated would save around 80 to 100 kg of
120 waste per 100 m² floor area (Mália et al., 2013).

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

123 Some European countries already achieved the objective of 70% recycling for CDW. Statistics show that the total
124 mass flow of recovered waste accounts for more than 80% of the total waste generation in Member States as the
125 Netherlands, Germany or Denmark (Eurostat, 2017). However, in some regions there is a significant amount of illegal
126 dumping and a heterogeneous market for secondary materials, which hinders the development of secondary materials
127 market, that may not be reflected in official statistics. For instance, high collection rates of well-segregated CDW are
128 achieved in Spain but the market uptake of recycled materials is really low; large storage areas at treatment plants
129 have essentially become temporary landfills (Joint Research Centre - European Commission, 2012).

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

136 **Figure 1. Construction and Demolition Waste’s Mineral fraction treatment in 2014 (Eurostat, 2017)**

137 Depending on the nature of the construction project, concrete waste ranges 40 to 85% of the total waste generated on
138 site (Rimoldi, 2010). Except for some elements such as beams or blocks, which can be *dismantled* from a building,
139 “clean” crushed concrete waste is barely re-usable and its recycling produces an usually downgraded product
140 (aggregates), as recovery of initial constituents from cement or the original aggregate is not feasible. Recycled
141 concrete aggregates, RCA, are usable for the so-called unbound applications (e.g. road sub-base fillings) or as
142 secondary materials in the manufacture of new concrete. Europe consumes around 2.6 billion Mg of aggregates
143 (European Aggregates Association, 2017). If the entire quantity of CDW is transformed into recycled aggregates,
144 only a 2% substitution of virgin aggregates would be achieved. In the UK, 6.4% of the aggregates for concrete came
145 from secondary sources or recycled materials in 2015 (The Concrete Centre, 2016). Therefore, there are no technical
146 barriers for a virtual 100% recycling of the main constituents of CDW, concrete and ceramic wastes, but barriers
147 derived from their commercialisation, the market of virgin materials or their logistics. A good example of these
148 barriers are observed in Spain, where, during 2017, 100 million Mg of aggregates were consumed in 2017 (ANEFA,

149 2017), but it is thought to correspond to an actual 22% of the total production capacity of the sector. On the other
150 hand, only 10 million Mg of CDW are generated, from which the current management system can generate up to 3
151 million Mg of usable recycled aggregate (FERCD, 2015); the impact of this secondary material in the total system
152 would only be 3% of the total aggregates market, but competing with the highly available resource of natural
153 aggregates.

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

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

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

176 **3. Best Environmental Management Practices for Construction and Demolition Waste**

177 *3.1. Methodology for the identification of Best Environmental Management Practices*

178 According to the EMAS regulation 1221/2009, a BEMP is the “most effective way to implement the environmental
179 management system by organisations in a relevant sector and that can result in best environmental performance under
180 given economic and technical conditions”. The identification of BEMPs is a process very similar to that for best
181 available techniques within the framework of the European Directive on Industrial Emissions, formerly Integrated
182 Pollution Prevention and Control (Schoenberger, 2009). In a first approach, data is collected from the literature,
183 industrial experience, and direct data and feedback from a technical working group of European experts. Performance
184 data is used to recognise best environmental management practices, while a deeper study is required to qualify the
185 selection of best practices regarding applicability and economic efficiency. In the case of the construction sector, a

186 technical working group of European experts, practitioners, regulators, constructors, developers, etc was established
187 at the beginning of the exercise. In a first meeting, the experts give recommendations and indications to the team of
188 the Joint Research Centre of the European Commission. The received information drives research on the topic, helps
189 organising site visits and experts are consulted. A first draft report is delivered to the technical working group, which
190 then ratifies, modify or comment on the list of best practices, the indicators used to measure their performance and
191 benchmarks of excellence where applicable.

192 The approach for the identification of BEMPs is further defined in other publications derived from EMAS sectoral
193 reference documents, e.g. for energy efficiency (Galvez-Martos et al., 2013), supply chain management (Styles et al.,
194 2012) in the retail trade sector, or water management in the hospitality sector (Styles et al., 2015).

195 3.2. *List of best practices*

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

201 **Table 3. Summary of best environmental management practices for CDW**

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

204 **Figure 2. Best environmental management practices for CDW management in the construction value chain**

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

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

214 3.3. *Waste management strategies*

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

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

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

227 In any case, there are examples where a whole strategy resulted in a rapid improvement from the BaU counterfactual
228 scenario: in the UK, the establishment of sound environmental policies and strategies around CDW through the Waste
229 Resources Action Programme, WRAP, contributed to the increase of the recycling rate up to 90% for the whole UK
230 (DEFRA, 2017), achieving exemplar cases with 100% concrete or metal wastes from construction sites diverted from
231 landfill, and achieving savings of more than 200 kg CO₂ per GBP 100,000 value of the construction (Institute of
232 Carbon and Energy, 2017). In the UK, the involvement of stakeholders was articulated using the “Halving Waste to
233 Landfill Commitment”, which involved more than 750 companies from the whole supply chain of construction
234 (Waste and Resources Action Programme, 2011).

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

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

243 As for any environmental policies, effective waste management strategies include a mix of complementary measures
244 such as regulatory, economic, educational and informative instruments (OECD, 2013; van Beukering et al., 2009).
245 In this context, **economic instruments** are designed to motivate waste producers to divert waste from landfills,
246 recycle more waste and optimise the use of resources, so waste is (i) prevented, (ii) well managed, and (iii) optimally
247 treated. These instruments can have greater impact than regulatory mechanisms, and introduce taxes or levies to the
248 polluter, linking the cost of waste treatment with the actual amount of waste generated by, for example, charging per
249 unit of waste. While these instruments have more recently been implemented for household waste streams, the
250 construction industry and CDW managers have extensive experience on these types of instrument, including landfill
251 taxes, aggregate levies or others. With regard to best practice, the business to business, B2B, schemes in Europe are
252 particularly remarkable. For instance, the existence of a B2B deposit refund scheme is sometimes a common practice
253 for highly re-usable packaging, like pallets, construction packaging, drums and others (Lundesjo, 2011; Waste and
254 Resources Action Programme, 2008a), and these practices have dramatically reduced the amount of waste generated
255 at construction sites. Although waste managers are not involved in this particular approach, they are key in the
256 management of the necessary reverse logistics, e.g. in construction consolidation centres.

257 At the local level, some municipalities have applied **traceability** requirements for CDW in their local licensing. For
258 example, municipalities in Spain are charging a deposit on the estimated amount of wastes reported in the site waste
259 management plan as part of the essential licensing requirement. The deposit is re-paid to the contractor when “waste

260 management certificates” are submitted to the authority. This particular deposit-refund scheme, managed by
261 municipalities, has potential to become a BEMP, but its current implementation does not meet BEMP requirements
262 for the following reasons:

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

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

- 275 - SWMP design. In this phase, the scope of the plan is developed, by e.g. identifying materials to be recovered,
276 re-used, recycled and disposed during construction or demolition. Waste management responsibilities are
277 defined, and the instruments for monitoring, collecting and promoting correct waste management practices
278 are identified, along with measurable indicators and targets. During the plan design phase, waste types will
279 be defined, estimated, and the waste management technologies will be sized. A first cost estimation will be
280 produced and potential savings will be identified. Procedures for removal, separation, storage, transportation
281 and any waste handling will be developed. A communication strategy should also be defined in a best practice
282 SWMP. During this phase, waste prevention techniques, re-use and recycling opportunities will be identified
283 per waste stream and their potential on-site application will be evaluated.
- 284 - SWMP implementation. Once the main procedures and strategies are defined, the waste manager responsible
285 for the site should communicate and explain the plan to all the relevant actors within the site and external
286 stakeholders affected by the site activity. The areas for waste storage and the available resources should be
287 well identified within the site, and waste containers should be placed as close as possible to the generation
288 point. Training and promotion of the plan should be regularly performed, especially with new contractors or
289 subcontractors, and a documentation file shall be kept updated.

290 3.4. *Prevention and collection*

291 In the building life cycle, wastes are generated from demolition material (of the previous construction on site),
292 damage of materials, off-cuts, design changes, temporary works materials, contamination of clean materials,
293 packaging, etc. Excavated materials and soils may be considered also as wastes if they are polluted or if for
294 administrative reasons they need to be managed as wastes. Approximately 33% of waste generation on a typical
295 construction site can be attributed to designers failing to implement waste prevention measures during the design
296 phase (Osmani et al., 2008), while the remainder can be considered unavoidable with current practices and

297 techniques. Table 5 shows some opportunities for *waste prevention during design*, i.e. **designing out waste** (adapted
298 from Waste and Resources Action Programme, 2012).

299 **Table 5. Waste prevention opportunities in the design phase**

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

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

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

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

- 322 • **Estimation of waste generation and provision of resources.** Best segregation options for a construction
323 site should be analysed in advance of the construction activity, so resources can be allocated for waste
324 management. The estimation of wastes generated during the construction activity should be based on a tailor-
325 made estimation (Martínez-Bertrand and Tomé, 2009), which should be optimised with the help of the
326 previous experience of the contractor.
- 327 • **Collection and segregation techniques.** Several collection techniques are needed to help site labourers to
328 perform correctly. Identified standard practices have the following common basis: (i) waste collection bins
329 are identified for each type of waste; the size of each bin or container is appropriate taking into account the
330 estimated amount to be generated, the number of containers and the foreseen number of waste deliveries; (ii)
331 waste collection bins are usually placed at the same point of the site (e.g. labelled as ‘ecopoint’, ‘recycling
332 point’, etc.); (iii) temporary collection points are usually placed next to a work position in order to increase
333 the efficiency of waste segregation, but which usually depends on the characteristics of the position; (iv)

334 hazardous wastes are collected in a separated point, protected from wind, rain and over a sealed surface with
335 the appropriate measures to prevent and minimise pollution of rainfall water; (v) all labourers, independently
336 if they come from the main contractor or a subcontractor are aware of the on-site waste management
337 techniques, (vi) there is enough space available for waste deliveries by truck; and (vii) waste collection points
338 are identified in a site plan and the plan is made available to all relevant actors.

339 • **Procedures and methodologies to ensure best management options.** These techniques usually refer to on-
340 site control techniques, such as visual inspection, computerised or photographic register, signs, symbols and
341 information, issuing and control of waste management certificates, and, in case it is required, pre-treatment
342 of waste is available on-site when high segregation rates need to be achieved, e.g. compactors, roll packers,
343 cardboard balers, shredders for wood, or portable crushers.

344 • **Provision of waste logistics.** Usually, two on-site collection methods are observed: reactive and scheduled.
345 For large fractions, such as inert fractions of CDW, a reactive collection is required, e.g. a full skip is
346 substituted by another empty skip on demand. For smaller volumes of wastes of constant generation, such as
347 those similar to municipal solid wastes, scheduled collection is the best option.

348 Best management practices on **material use** refer to logistics schemes that optimise material use by minimising the
349 amount of raw materials stored on site, which reduces the likelihood for supplied materials to become waste. In
350 traditional logistics, the majority of materials are stocked when they arrive on a construction site. This means that
351 materials are double handled, increasing the risk of damage and the rate of waste generation along with the subsequent
352 cost. In this sense, *stockholding* is a term defined as the process of holding materials in readiness for subsequent
353 activities (Constructing Excellence, 2006). Material use efficiency can avoid environmental impacts because: less
354 fuel is consumed if less material is transported, less materials leftovers are produced if stockholding is reduced down
355 to a minimum, etc.

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

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

367 3.5. *Re-use of materials*

368 From the circular economy point of view, the best re-use option in the construction sector is the re-use of the entire
369 building. Factors such as space, integrity, aesthetics, refurbishment costs and client satisfaction play a key role on
370 the feasibility assessment of the potential of building re-use (Institute of Civil Engineers, 2008). In many cases, the
371 most economic option will be the demolition of buildings, which, as traditionally conceived, produces large amounts

372 of demolition waste that often results in a significant portion of the total waste stream. **Selective building**
373 **deconstruction** is an alternative to demolition that involves a systematic disassembly with the objective of
374 maximising re-use, recycling and diversion from landfill.

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

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

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

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

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

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

403 3.6. *Waste treatment and material recovery*

404 Current **CDW processing and recycling techniques** can be considered well established and their implementation is
405 common across Europe. However, the nature of the final secondary materials and the market penetration differ
406 widely. A common CDW recycling plant usually consists of (1) reception, weighing and visual inspection, (2) manual
407 preselection (for unsegregated streams), rejection and diversion to alternative treatments, (3) screening of large

408 materials, (4) magnetic separation, (5) manual separation of plastic, wood and other waste streams if required, (6)
409 crushing, and (7) screening and secondary crushing, which is applied depending on the goal product mix.

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

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

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

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

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

438 **Table 7. Possibilities for recycled construction materials.**

439
440 The use of RA and RCA helps to reduce the use of virgin materials from quarries, which usually have a high
441 environmental impact at local level. For example, the German regions of Berlin and Baden-Württemberg achieve
442 recycling rates higher than 90% for CDW, which can be attributed to the existence of proper standards and
443 environment regulations (APPRICOD (Assessing the Potential of Plastics Recycling in the Construction and
444 Demolition Activities), 2006; QRB, 2009). From the life cycle perspective, the use of recycled aggregates produces

445 a net reduction in the CO₂ emissions and primary energy consumption, since the extraction of virgin materials is
446 avoided, but some trade-offs must be taken into account. For instance, regarding the health and safety issue in
447 recycling plants, at least 20 to 25% of dust in the surroundings of recycling plants has been detected to be of a
448 diameter of less than 10 µm (Kummer et al., 2010) and, therefore, its release should be duly controlled, e.g through
449 the implementation of de-dusting devices in screening, crushing and handling operations. Also, the location of
450 recycling plants close to urban areas, although good in terms of life cycle environmental impact, has an adverse effect
451 due to noise, vibration and emissions from the commonly used diesel engines.

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

458 In order to achieve a less heterogeneous management landscape on the management of hazardous CDW in Europe,
459 the European Commission mandated CEN for harmonisation on the assessment of dangerous substances. As a
460 response, a new Technical Committee – CEN/TC 351 – was created: ‘Construction products: assessment of release
461 of dangerous substances’. This committee will provide tools and assessment methods for the quantification of
462 dangerous substances, which may be released from construction products to the environment into the soil, ground
463 water, surface water and indoor air (Ilvonen, 2013). In this respect, an important aspect of the hazardous potential of
464 CDW is the leachability of chemicals from produced RA. It is common that RA coming from ashes, slags and other
465 wastes are well regulated regarding their composition, while for recycled concrete some countries apply a set of
466 different criteria. For instance, the Netherlands does not apply a waste regulation to RA, but a common regulation is
467 used for natural or RA in terms of environmental criteria.

468 **Quality assurance schemes** have become a key element for the marketing of secondary materials produced from
469 CDW recycling. The construction industry, in general, has a very conservative approach to innovation, which is
470 basically due to its traditional behaviour and the legal liability of architects, engineers, developers and contractors
471 regarding their final products (Zeschmar-Lahl et al., 2016), so construction stakeholders rely on sound standards to
472 support advances. On the other hand, RAs have usually had a low- grade application, e.g. as backfilling material for
473 quarries, some sub-base applications for road and cover for landfills. But, it is well known that certain qualities of
474 RA or RCA fit higher grade applications, e.g. as aggregate material in concrete for structural and non-structural
475 applications. A quality assurance scheme, in this context, would establish common rules for producers and, very
476 importantly, would increase the confidence of final users. A best practice quality assurance scheme is one that drives
477 increased uptake of RAs and RCAs, following a voluntary agreement approach, rather than regulation, including all
478 stakeholders along the construction value chain. Among many measures, it should include waste segregation and
479 diversion from landfill, while defining environment-related criteria, e.g. as leaching characteristics and reference
480 standards, and awarding, if possible, an End-of-Waste or by-product character to the secondary material produced.
481 For instance, based on well-defined protocols and procedures, the region of Baden-Württemberg in Germany
482 classifies three quality levels for RAs based on their leaching characteristics, and defines suitable applications for

483 each classification (QRB, 2009). Delgado et al., 2009, collected information from some frontrunner quality assurance
484 schemes in Europe, such as the Austrian construction materials recycling association, the region of Flanders, the SFS
485 standard 5884 in Finland, or the programme Aggregain in the UK, established by WRAP. Although it is out of the
486 scope of this paper to discuss the suitability of environmental performance standards, the lack of harmonisation in
487 Europe regarding RA is remarkable and problematic. It was noted that current requirements in many Member States
488 of the European Union are less restrictive for virgin materials than for those secondary materials consisting on RA
489 (Saveyn et al., 2014). Regarding the performance of RA, the most important standard is the European EN 12620
490 under approval (CEN (European Committee for Standardization), 2013), which specifies the properties of aggregates
491 regardless of the origin. This standard is an attempt to standardise, under the current construction products regulation
492 (European Parliament and the Council, 2011) a harmonised set of quality requirements. Other standards are
493 applicable for roads (EN 13242) or asphalts (EN 13043).

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

502 The importance of plasterboard segregation and its impact on the whole CDW reprocessing is of high relevance. A
503 separate thematic area was set up by WRAP in the UK, where several local authorities introduced waste plasterboard
504 collection at their Household Waste Collection centres, e.g. Sheffield (Waste and Resources Action Programme,
505 2009). Also, at European level, the project GypsumToGypsum (Marlet, 2017) aimed to integrate better the supply
506 chain of gypsum-based products by closing the loop and to increase the quantity of gypsum-based waste being
507 diverted from landfill for recycling. Europe demands around 15 million Mg of plasterboard, and the annual
508 production of its waste is around 2.35 million Mg. So, therefore, there is more than enough capacity for recycling.

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

- 510 • Plasterboard panels are subject of designing-out waste practices, since proper sizing and just-in-time
511 practices would reduce the amount of wasted plasterboard considerably.
- 512 • Plasterboard is a durable product, so panels and tiles made of plasterboard, with no damage, can easily be
513 reinstalled (re-used).
- 514 • The product itself can incorporate secondary material up to virtually 100% of the raw material, although the
515 industry tends to use natural gypsum. E.g. in Germany the demand for the construction material gypsum is
516 mainly fulfilled (currently at least 60%) by gypsum as a side product of the flue gas desulphurization in the
517 electricity production process at coal power plants.
- 518 • Reprocessing waste plasterboard can produce gypsum of high quality, according to certain standards, with a
519 variety of potential uses apart from new plasterboard: raw material for cement manufacture, roads sub-base,
520 and soil improvement for agriculture. The characteristics of each secondary product are defined in quality

521 assurance schemes e.g. for the UK. In general, the presence of fibres in the waste limits its applicability to a
522 25% of the total raw meal for new plasterboard.

- 523 • Waste plasterboard segregation benefits other CDW recycling, as sulphates, generally coming from
524 plasterboard, are mixed with other CDW fractions in unsorted waste management, which prevents the
525 application of the recycled aggregate.

526 3.7. *Applicability, economics, and achievable environmental benefit*

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

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

534 4. Final remarks

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

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