Best practices for the management of end-of-life gypsum in a circular economy

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Abstract

While gypsum can effectively be recycled, most gypsum waste (GW) is currently landfilled in the European Union. In order to achieve higher recovery rates and promote a closed-loop supply chain, it is necessary that stakeholders can implement best practices, in particular from waste production to waste processing, processes that are part of the end-of-life (EoL) stage. In this stage, waste production cannot be reduced, and therefore the priority should be to appropriately collect and recover EoL products. The aim of the paper is to investigate best practices for the management of EoL gypsum in a circular economy. To achieve this, best practices for the management of EoL construction products are selected from the literature, adapted to the case of EoL gypsum and subjected to stakeholder consultation. Results revealed significant differences in the waste management practices between two target groups: gypsum recycling and non-gypsum recycling countries. It is concluded that three best practices are fundamental to promote a circular economy for gypsum products: on-site segregation of GW, clear waste acceptance criteria and clear recycled gypsum quality criteria.

Keywords: construction sector; deconstruction; resource efficiency; circular economy; lean value chain; secondary raw materials.

Highlights

- Practices for closing the loop of gypsum products in a circular economy are identified
- Stakeholders' views on best practices are explored
- Three best practices are proposed as fundamental to enable gypsum recycling.

1. Introduction

The destination of end-of-life (EoL) construction products is diverse (re-use, recycling, other recovery or disposal) and those treatments that demonstrate the best environmental performance should be encouraged (European Parliament and the Council of the European Union, 2008). These EoL products (also known as demolition and renovation waste) are increasingly generated in the European Union (EU), as the building stock increases and buildings approach the end of their service life (Buildings Performance Institute Europe (BPIE), 2011). Therefore, building products reach the EoL stage and become EoL products. It is estimated that 46%

of the construction and demolition (C&D) waste produced in the EU is re-used or recycled (European Commission (DG ENV), 2011). For the case of EoL products alone, EU data is not available. In all cases, recycling involves avoiding losing resources and achieving the 70% recovery target by 2020 (European Parliament and the Council of the European Union, 2008). However, more than half of the potential raw materials resources are either incinerated or dumped in landfills (European Commission (DG ENV), 2011), which entails a loss of resources. In order to change this current situation, alternatives to the common EoL practices should be considered and assessed, in order to identify the ones that close the material loop while improving the environmental performance (Silvestre et al., 2014).

EoL construction products are mainly composed of inert products (e.g. concrete, ceramic), along with small quantities of non-inert ones, such as wood, packaging waste and gypsum waste (GW). In particular, GW makes up between 0.2% and 0.4% by weight of the total C&D waste composition (European Commission (DG ENV), 2011). Although gypsum comprises a small proportion of the total waste, gypsum landfilling commonly entails hydrogen sulphide and higher greenhouse gas emissions (Jiménez Rivero et al., 2016). On the contrary, gypsum recycling contributes to achieve the 70% recovery target above mentioned.

Adopted practices by stakeholders at the EoL stage commonly determine the fate of EoL gypsum products. The EoL stage (CEN, 2012) of gypsum for recycling starts with deconstruction (or selective demolition, as opposed to the conventional un-selective demolition), transport of the post-consumer GW and processing. Therefore, various stakeholders should cooperate in this stage (e.g. contractors, waste collectors, gypsum recyclers and manufacturers). For example, inadequate practices at the deconstruction site may convert recyclable GW into a non-recyclable material (i.e. non-compliance with the waste acceptance criteria, see Section 2.15).

The notion of best practices has been used by many authors and in many contexts. Traditionally, best practices have commonly focused on the quality and competitiveness of business processes (Heibeler et al., 1998; Szulanski, 1996; Ward, 1997; Zairi, 1997). Best practices are currently applied in other contexts too, such as new products development, ecosystem restoration, recycling networks and waste management improvement (Barczak and Kahn, 2012; Eleftheriadis and Myklebust, 2015; Farel et al., 2013; Kurdve et al., 2014; Mansar and Reijers, 2005; Rose et al., 2015; Rossi et al., 2012; Villoria Saez et al., 2013). Increased knowledge on the best practices for EoL gypsum may lead to appropriate stakeholders' decisions for promoting recycling. Moreover, sharing of best practices is considered vital for success (Zutshi and Creed, 2014).

A number of recent studies on C&D waste have thoroughly analysed measures for successful management strategies (Begum et al., 2009; Poon et al., 2001; Tam, 2008; Villoria Saez et al., 2013; Wang et al., 2010). More recently, the best practice of prefabrication implementation was evaluated by Tam et al. (2014), as a strategy to induce waste reduction. However, little attention has been paid to the peculiarities of different waste streams (e.g. non-inert non-hazardous waste such as gypsum) and the EoL stage (e.g. renovation and deconstruction works). In this stage, strategies to prevent or reduce EoL products cannot be applied and thus the collection for re-use or recycling should be prioritized. Therefore, this study focuses on the EoL stage, from deconstruction to the production of quality secondary raw materials, of a non-inert waste fraction: gypsum. This work proposes a set of best practices for the management of EoL gypsum in a circular economy.

The concept of circular economy involves principles from several schools of thought, such as the cradle to cradle design (McDonough and Braungart, 2002), biomimicry (Benyus, 2002) and the performance economy (Stahel, 2010). The concept can be summarized in three principles for action, related to the preservation of natural resources, the optimization of resource yields and the effectiveness of the system (Ellen MacArthur Foundation, 2016). In accordance with them particular actions are to be taken in each step of the value chain, i.e. production, consumption, waste management and production of secondary raw materials, as formulated in the EU Action Plan for the Circular Economy (European Commission, 2015). The scope of this paper is limited to the steps "waste management" and "production of secondary raw materials". To this end, a set of 23 best practices were outlined (see Section 2) and subjected to stakeholder consultation (as described in Section 3). Finally, data analysis of the survey results yielded a selection of the fundamental practices at EU level. It should be noted that best practices in this study are designed to operate at the micro-level (i.e. a particular deconstruction-recycling value chain), in contrast to factors influencing the fate of GW at EU or country level (i.e. at the macro level). On the one hand, the already identified factors provide a framework for decision-makers to improve the functioning of the gypsum value chain (Jiménez-Rivero and García-Navarro, 2017). On the other hand, the best practices studied here aim to guide stakeholders of the deconstruction-recycling value chain (construction agents, recycling agents and manufacturers) towards embracing a circular economy for EoL gypsum.

2. Selected best practices for the management of EoL gypsum in a circular economy

Best practices for closing the loop of EoL construction products were identified from the literature, and adapted to the case of gypsum when required. Additional practices were defined as a result of findings from the European Life+ Gypsum to Gypsum (GtoG) project "From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry" (GtoG project, 2013), which framed this investigation (see Table 1). The practices are grouped under four codes: deconstruction (DE), recycling (RE), manufacturing (MA) and general (GE). The code assigned to each practice includes these abbreviations (e.g. best practice DE3 belongs to the category "Deconstruction"). It is worth noting that some of the practices are interrelated and benefit each other. For example, when a precise site waste management plan (DE4) operates, the number and size of containers needed (DE9) should be planned, and the number of round-trips from deconstruction to the recycling plant are likely to be minimized (DE10). These connections are explained, along with the description of each practice, in sub-sections 2.1-2.23 below.

Table 1.Selected practices for the management of EoL gypsum in a circular economy

Code	Best practice	Source
DE1	Plan coordination and review meetings	Faniran and Caban, (1998), Formoso et al. (2002), Lönngren, Rosenkranz, & Kolbe (2010), Lu and Yuan (2010), Villoria Saez et al. (2013), Antink et al. (2014) and Calvo, Varela-Candamio, Novo-Corti (2014)
DE2	Appointment of a worker responsible for the follow-up of the waste management	Lu and Yuan (2010) and Villoria Saez et al. (2013)
DE3	Implement an effective pre-deconstruction audit	Chini and Bruening, (2003), Hurley (2003), Delgado et al. (2009), Singapore Government, HISER project - H2020 under agreement No. 642085
DE4	Draft and implement a precise site waste management plan (SWMP)	WRAP (2011) and Ajayi et al. (2015)
DE5	Train workers concerning gypsum products dismantling, as well as sorting and storing of GW	Shen and Tam (2002), Tam (2008), Begum et al. (2009) Lu and Yuan (2010) and Villoria Saez et al. (2013)
DE6	Appointment of trained workers	WRAP (2007), CIB (2014) and Ajayi et al. (2015)
DE7	Perform an on-site segregation of GW	Poon et al. (2001), Tam (2008), del Río Merino, Izquierdo Gracia, and Weis Azevedo (2010), Lu and Yuan (2010), Wang et al.(2010) and Villoria Saez et al. (2013) and Ajayi et al. (2015)
DE8	Effective planning of GW capture systems	WRAP (2007)
DE9	Plan number and size of containers needed	Llatas (2011), del Río Merino, Izquierdo Gracia, and Weis Azevedo (2010) and Villoria Saez et al. (2013)
DE10	Minimize number of roundtrips to recycling	GtoG project (2015c)
DE11	Perform GW traceability, from source to final destination	Lu, Huang, and Li (2011), Deloitte (2015), Wilson et al. (2014)
RE1	Recycling plant or warehouse strategically located	Beamon and Fernandes (2004), Kourmpanis et al. (2008), Banias et al. (2010), Calvo, Varela-Candamio, Novo-Corti (2014)
RE2	Have an adequate warehouse for GW and RG storage	GtoG project (2015c)
RE3	Operate a quality management system	Council of the European Union (2011); Villanueva and Eder (2011), EC (2012) and EC (2013)

RE4	Set clear waste acceptance criteria	Tukker et al. (1999), Delgado et al. (2009), Agrela et al. (2011), WRAP and BSI (2013)
RE5	Perform effective sorting operations prior to GW processing	GtoG project (2015c)
RE6	Prepare a schedule of sampling and test frequencies for each quality criteria parameter	Villanueva and Eder (2011); WRAP and BSI (2013)
RE7	Agree suitable supply contracts between recyclers and manufacturers	WRAP and BSI (2013), GtoG project, (2015c)
MA1	Set clear RG quality criteria	Bundesverband der Gipsindustrie e.V. (2013), WRAP and BSI (2013)
MA2	Promote plasterboard take-back schemes	AEA Technology Plc (2006), WRAP (2006) and Nnorom and Osibanjo (2008)
MA3	Set a RG reincorporation target	GtoG project (2015c)
GE1	Address the end-of-waste (EoW) status	Villanueva et al. (2010), Delgado et al. (2009), The Council of the European Union (2011), The European Commission (2012), The European Commission (2013), Hjelmar et al. (2013)
GE2	Availability of suitable close-top skips	GtoG project (2015c)

DE: deconstruction; RE: recycling; MA: manufacturing; GE: general. GW: gypsum waste; RG: recycled gypsum

2.1. Plan coordination and review meetings (DE1)

Coordination among agents has been traditionally considered during the design (Formoso et al., 2002), from design to construction (Faniran and Caban, 1998; Lu and Yuan, 2010), and from design to use stage (Lönngren et al., 2010). Here we propose regular communication among agents involved in the EoL stage. Such coordination allows revision of coordination measures, identification of problems to be overcome, discussion of procedures and schedules as well as requirements for recovery operations, in compliance with the SWMP, where it exists (see DE4). Antink et al. (2014) warns about the lack of coordination among agents in the construction sector, which is also identified by Calvo et al. (2014) as one of the main social barriers for C&D waste management.

2.2. *Appointment of a worker responsible for the follow-up of the waste management (DE2)*

The follow-up of waste management typically includes on-site C&D waste supervision, such as periodic checks on storage areas or the use of containers (Lu and Yuan, 2010; Villoria Saez et al., 2013). Moreover, traceability checks should be encouraged (e.g. delivery notes from source to final destination). GW containers should be covered at the end of the day in order to reduce potential moisture and impurities.

2.3. Implement an effective pre-deconstruction audit (DE3)

An accurate (i.e. minimum deviation between waste foreseen and generated) pre-deconstruction audit, also referred as pre-demolition inventory or building inventory, should describe the waste fractions to be generated (e.g. type, opportunities to reuse or recycle), amount, location and expected recovery rates. When properly prepared, the pre-deconstruction audit becomes a planning tool for the deconstruction work (Delgado et al., 2009, HISER project - H2020 under agreement No. 642085, n.d.; Singapore Government, n.d.). In this way, the uncertainty on what systems will be found when dismantling is reduced (Delgado et al., 2009). Such waste prediction will set the basis for the development of a sound site waste management plan (see DE4), which in turn will result in increased recovery options of materials, along with the potential cost savings associated. Examples of existing site waste management tools include the Demolition Protocol in Singapore (Singapore Government, n.d.) and the Site Methodology to Audit Reduced Target Waste (SMARTWaste) in the UK.

2.4. Draft and implement a precise site waste management plan (SWMP) (DE4)

A typical SWMP involves waste prevention and management strategies before, during and after the construction works (Ajayi et al., 2015). This document can be applied in any construction, excavation or demolition activity (e.g. new construction, maintenance, deconstruction, excavation, alteration, civil engineering and decoration works). Focusing on EoL products, an outstanding SWMP should go beyond legislative compliance and contain a precise waste forecast (which can be known after Implementing an effective pre-deconstruction audit, see DE3), plan how to reuse and then recover the forecasted waste (i.e. specify waste carriers, plan waste destinations, waste management and recovery actions), implement and monitor the plan (i.e. record actual waste movements) (Ministerio de la Presidencia, 2008; WRAP, 2011). The document should be updated during the course of the project, recording how waste is actually managed and the deviation with the waste foreseen. Currently, these plans are mainly prepared to fulfil legal requirements (e.g. in Spain it is regulated by the Royal Decree 105/2008) or the requirements of an evaluation tool (e.g. BREEAM or LEED).

2.5. Train workers concerning gypsum products dismantling, as well as sorting and storing of GW (DE5)

On the one hand, the development of C&D waste management awareness is a lengthy process that requires vocational worker's training and education (Lu and Yuan, 2010). On the other hand, skills on dismantling can be easily learned (essentially deconstruction follows the reverse order of construction; for further insight into deconstruction see CIB, 2000). Providing in-house and periodic training can be an effective measure to enrich waste management knowledge training for different levels of employees (Shen and Tam, 2002; Tam, 2008). Begum et al. (2009) found that the participation in waste management training programmes cause positive attitudes towards waste management.

2.6. Appointment of trained workers (DE6)

Trained workers in waste dismantling, sorting and storing (see best practice above, DE5) should be appointed for proper dismantling, source separation and subsequent storage. By way of illustration, noticeable time savings are achieved when placing GW straight into the containers that will be collected by the waste carrier, rather than stockpiling the waste first and collect it later on (WRAP, 2007). In any case, workers dedicated to sorting operations were found to successfully impact recycling operations (Ajayi et al., 2015).

2.7. Perform on-site segregation of GW (DE7)

On-site segregation, also known as on-site sorting, source separation or source segregation, refers to the process of sorting different EoL products after dismantling, and should be followed by separate collection. On-site segregation of C&D materials has been largely studied as a waste management measure (Poon et al. 2001, Tam, 2008; del Río Merino et al., 2010; Lu and Yuan, 2010; Villoria Saez et al., 2013; Wang et al., 2010) and as a waste management strategy to divert waste from landfills (Ajayi et al., 2015). In particular, on-site segregation of EoL gypsum allows minimum levels of impurity and therefore the generation of greater amounts of recyclable GW. If the waste owner cannot perform this operation (e.g. due to the lack of physical space), a transfer station, where segregation can be applied, should be used.

2.8. Effective planning of GW capture systems (DE8)

Effective planning and implementation of GW capture systems limits manual handling operations (see WRAP (2007) for schematics of different capture systems such as the chute to skip system and the hoist and bag system). Their successful use depends on peculiarities of each construction site. These peculiarities should be carefully examined in order to design adequate systems (WRAP, 2007).

2.9. Plan number and size of containers needed (DE9)

In order to plan the needed containers, the estimated volume of waste, calculated in the pre-deconstruction audit (see DE3) and SWMP (see DE4) prior to commence of the deconstruction works, is valuable information. From that estimation, the number and size of containers considering the amount of storage space needed can be planned for an efficient collection frequency (Llatas, 2011). In this way, GW storage and roundtrips (see DE10) to the final destination are optimized, at the same time that recycling and recovery options are increased. This entails economic and time savings.

2.10. Minimize number of roundtrips to recycling (DE10)

The number of roundtrips can be minimized when coordination (see DE1) and traceability (see DE2 and DE11) measures are followed, commonly framed in the waste management plan (see DE4). The frequency for containers' collection should be planned in advance, ensuring that, whenever possible, only full containers are transported whilst preventing containers from overfilling. In addition to these measures, selecting a warehouse or recycling plant strategically located, GHG emissions derived from the transport distances travelled are kept as minimal as possible (Jiménez-Rivero and García-Navarro, 2016).

2.11. Perform GW traceability, from source to final destination (DE11)

Tracking waste materials promotes transparency and quality assurance. Proper traceability of waste involves planning in advance waste carriers and recovery routes, register and keep records of GW amounts and control them. A voluntary initiative, called Tracimat, has been found in the Flemish region (Belgium), aiming to help with C&D waste fractions traceability from January 2016 (Deloitte, 2015). This practice can be performed by the worker appointed for the follow-up of the waste management (see DE2).

2.12. Recycling plant or warehouse strategically located (RE1)

Warehouses and recycling plants store both GW (received from construction sites, public recycling centers, collectors, etc) before processing it, as well as the resulting RG (to be transported to the final costumer, e.g. plasterboard manufacturers). Therefore, the location and number of gypsum recycling plants or warehouses are considered crucial for minimizing GHG emissions (see also DE10) and costs, which can incentivize deconstruction companies to prioritize the recycling route or even determine the fate of the waste. Besides, a suitable route should take into consideration to minimize impacts from a social and environmental perspective as well (e.g. local ecosystem disturbance, traffic burden) (Banias et al., 2010).

2.13. Have an adequate warehouse for GW and RG storage (RE2)

A properly dimensioned and covered storage place should be set up in order to guarantee a constant GW feedstock. Storage areas should be maintained in accordance with the quality assurance system requirements (see RE3) in order to ensure that external contamination and free moisture are prevented (considering the RG quality criteria as detailed in MA1). Experienced gypsum recyclers in the GtoG project reported a coefficient of expansion of 0.4 t/m^3 for GW and 0.7 t/m^3 for RG (GtoG Project, 2015).

2.14. Operate a quality management system (RE3)

A quality assurance system is an important tool to demonstrate compliance with the RG quality criteria established and to create reliability on the end-of-waste criteria, if existing. For this purpose, an internationally recognized and externally verified quality management system (QMS), such as ISO 9001 or similar may be operated.

Considering the criteria laid down in other industries (The Council of the European Union, 2011; The European Commission, 2013, 2012), a suitable QMS for GW is expected to include the acceptance control of GW, monitoring of the treatment process, monitoring of the quality of the resulting RG, feedback from costumers concerning compliance with RG quality, record keeping, review and improvement of the management system as well as training of staff.

2.15. Set clear waste acceptance criteria (RE4)

Waste acceptance criteria (WAC) at the recycling plant or warehouse, also referred as criterions of acceptance (Agrela et al., 2011), should apply to the waste used as input for gypsum recycling. The acceptance control of waste is commonly performed in compliance with these criteria (The Council of the European Union, 2011; The European Commission, 2013, 2012) WAC should be communicated to costumers to develop their management system in line with the WAC, while at the same time facilitating the acceptance control of GW.

2.16. Perform effective sorting operations prior to GW processing (RE5)

The source of GW usually determines the level of impurities. For example, pre-consumer GW requires less sorting than EoL gypsum. The presence of impurities in the accepted waste is typically limited to 2%. Although recycling units are usually equipped with separation technology, a preliminary sorting is typically required in order to minimize the risk of machine breakdown or avoid lower RG quality. Sorting techniques reported by actual gypsum recyclers consist on visual manual sorting (GtoG project, 2013b).

2.17. Prepare a schedule of sampling and test frequencies for each quality criteria parameter (RE6)

Monitoring frequencies should be documented as part of the QMS and should be available for auditing. In addition, sampling results should be recorded, kept for the competent authorities and made available on their request. The sampling procedures and calibration methods shall be also made available for auditing (Villanueva and Eder, 2011; WRAP and BSI, 2013).

2.18. Agree suitable supply contracts between recyclers and manufacturers (RE7)

Supply contracts should be agreed in a collaborative manner. The required information should be obtained, supplied and retained in order to demonstrate, when requested, that RG supplied is destined for appropriate use (WRAP and BSI, 2013).

2.19. Set clear RG quality criteria (MA1)

Existing quality criteria for RG are country-specific and even company-specific. Examples of different quality criteria currently found in the EU are: the RG initial test for recycling plants in Germany (Bundesverband der Gipsindustrie e.V., 2013), PAS 109:2013 in the UK (WRAP and BSI, 2013), as well as other commercial specifications developed by gypsum recyclers, plasterboard manufacturers or Eurogypsum Member Associations. The GtoG project has produced a set of European voluntary guidelines on the RG quality criteria for the gypsum industry, covering technical and toxicological criteria (GtoG project, 2015b).

2.20. Promote plasterboard take-back schemes (MA2)

Extended producer responsibility schemes are adopted in many fields to promote collection and recycling of waste, close the material loop and incentivize ecodesign (Richter and Koppejan, 2015). Increasingly, countries are putting in place “take-back” laws, which require that the manufacturer takes-back the used product at its EoL (Nnorom and Osibanjo, 2008), as recovery and recycling are guaranteed this way. Currently, gypsum products take-back is not mandatory, and thus only voluntary take-back schemes exist (AEA Technology Plc and WRAP, 2006; WRAP, 2006).

2.21. Set a RG reincorporation target (MA3)

The establishment of corporate objectives on environmental sustainability, particularly addressing RG content, promotes closed-loop gypsum recycling. This target may be part of the manufacturer’s corporate social responsibility (GtoG Project, 2015).

2.22. Address the end-of-waste (EoW) status (GE1)

The removal of the waste status can promote the quality of the resulting secondary raw material, which may increase their demand (Delgado et al. 2009). EoW criteria for the production and use of RG from plasterboard waste are only a reality in the UK, governed by the Quality Protocol (WRAP and Environment Agency 2013).

2.23. Availability of suitable closed-top skips (GE2)

Closed-top skips are preferentially recommended for GW storage in order to protect waste from wet weather and minimize free moisture.

3. Methodology: stakeholder consultation

A questionnaire (see Appendix A - Questionnaire) was used to investigate stakeholders' views on the selected best practices to successful management (see Section 2). The online questionnaire was designed and conducted between September and December 2015. Before being launched, the survey was pre-tested in an expert meeting conducted in October 2015 with a group of eight experts, participants of the GtoG project. As a result, the descriptions of the questions were fine-tuned and a new practice was included: "Availability of suitable closed-top skips (GE2)" (see Section 2). In this meeting, the consultation strategy was also defined (i.e. GtoG partners in charge of translating the survey and timeline to collect responses and analyse data). The questionnaire was prepared in English, French, German and Spanish, with the aim to reach the maximum number of responses.

The questionnaire was distributed among 152 stakeholders. Efforts were made to ensure a high response rate. These included a personalized accompanying email, information on the confidentiality clause in the GtoG project consortium agreement and follow-ups of all non-respondents. Respondents were required to rate each practice on a 5-point Likert-type scale, in terms of importance (i.e. influence of the given practice on closing the loop of gypsum products), implementation (i.e. current probability of occurrence of the given practice in respondents' national context) and feasibility (i.e. the extent to which they can be applied or put in practice). Two separate sections formed part of the questionnaire: deconstruction and processing/reincorporation. At the end of each section, space was provided to accommodate comments. The questionnaire also contained a general data part.

A total of 58 responses (*N=58*) were gathered from stakeholders working in gypsum recycling (GR) and non-gypsum recycling (NGR) countries. These stakeholders included manufacturers (16%), construction agents (34%), waste collectors and gypsum recyclers (19%) as well as other stakeholders (researchers (16%) and public institutions and associations (16%)). While 62% of them (*N*=36) perform their activity in GR countries (Belgium, Denmark, France, Netherlands and United Kingdom), 48% (*N*=22) work in NGR countries (Austria, Germany, Greece, Portugal and Spain). Respondents working at European public institutions and associations were considered in the GR countries group. A 38% response rate was achieved.

The analysis, performed using SPSS v23, included descriptive statistics (central tendency: mean, median and dispersion: standard deviation) and the Mann-Whitney U test, a non-parametric test that compares distributions of responses between groups (Harpe, 2015), at 95% confidence interval. In the Mann-Whitney U test the null hypothesis is rejected if the observed p-value is less than the significance level (α=0.05). Moreover, Cronbach's alpha coefficient was assessed to check the internal consistency of the scale. The alpha values were 0.942 (importance scale), 0.934 (implementation) and 0.965 (feasibility). As these values are above 0.8, the scale can be considered reliable with our sample (Carmines and Zeller, 1979). Best practices were ranked according to their mean value (M), an approach commonly adopted in construction management research to evaluate Likert-type scales (Ali et al., 2013; Lu and Yuan, 2010; Poon et al., 2001; Villoria Saez et al., 2013; Wang et al., 2010). M can be expressed as follows: $M = \sum_{y=1}^{5} N_{xy} S_y / \sum_{y=1}^{5} N_{xy}$, where N_{xy} is the number of stakeholders that chose the yth score (S_y) for the xth best practice and S_y is the score given by stakeholders for each best practice.

The identification of practices commonly applied in GR but not yet adopted in NGR countries permitted to propose fundamental practices to enable gypsum recycling. The cut-off mean value was set at 4.00. Moreover, current implementation above 70% in GR countries was required (see Fig. 2) in order to be considered a fundamental practice.

4. Results and discussion

Table 2 summarizes the analysis on the importance given by stakeholders (see Section 3 for details on the selected statistics). Practices are ranked (from highest to lowest mean) according to the mean value on importance from GR countries, due to their experience in leading approaches for the achievement of an improved deconstruction-recycling value chain. The higher the mean value, the higher the stakeholders valued the practice. In addition, results from the Mann-Whitney U test are shown, which are useful to determine statistical difference between how the stakeholders working in GR and GNR countries view the selected practices.

Table 2. Results of the questionnaire survey on the importance of best practices

No.	GR countries				NGR countries					Mann-Whitney	
	M	SD	Mdn	Rank	No.	M	SD	Mdn	Rank	Z	p
RE4	4.67	0.48	5.00	1	RE4	4.13	1.30	5.00	6	-0.953	0.341
DE7	4.64	0.90	5.00	2	DE7	4.25	1.00	5.00	4	-1.591	0.112
RE5	4.58	0.58	5.00	3	RE5	4.07	1.07	4.00	7	-1.699	0.089
RE2	4.48	0.51	4.00	4	RE2	3.94	1.18	4.00	12	-1.318	0.187
MA1	4.48	0.81	5.00	5	MA1	4.19	1.28	5.00	5	-0.336	0.737
RE1	4.39	0.66	4.00	6	RE1	3.88	1.36	4.00	13	-0.938	0.348
DE2	4.32	0.57	4.00	7	DE2	4.00	1.13	4.00	9	-0.611	0.541
DE3	4.25	0.72	4.00	8	DE3	3.69	1.14	4.00	17	-1.524	0.128
DE5	4.23	0.75	4.00	9	DE5	3.94	1.37	4.00	11	-0.682	0.495
RE3	4.23	0.92	4.00	10	RE3	3.80	1.12	4.00	14	-0.728	0.467
DE1	4.21	0.85	4.00	11	DE1	4.33	0.72	4.00	2	-0.321	0.748
DE11	4.19	1.03	4.00	12	DE11	2.93	1.28	3.00	23	-2.923	0.003
DE4	4.09	1.06	4.00	13	DE4	3.94	1.06	4.00	10	-0.516	0.606
DE9	4.05	1.09	4.00	14	DE9	3.69	0.63	4.00	18	-0.718	0.473
DE10	4.05	0.90	4.00	15	DE10	3.75	1.14	4.00	16	-0.866	0.387
RE7	4.05	1.05	4.00	16	RE7	4.40	1.18	4.00	1	-0.792	0.429
MA3	4.00	1.00	4.00	17	MA3	3.44	1.41	3.50	21	-1.163	0.245
RE6	3.96	0.82	4.00	18	RE6	4.07	0.83	4.00	8	-0.512	0.608
MA2	3.95	0.95	4.00	19	MA2	4.27	1.10	5.00	3	-1.267	0.205
DE8	3.95	1.24	4.00	20	DE8	3.56	1.15	4.00	19	-1.190	0.234
GE1	3.85	1.09	4.00	21	GE1	3.42	0.96	4.00	22	-1.564	0.118
GE2	3.71	1.20	4.00	22	GE2	3.45	1.15	3.50	20	-0.858	0.391
DE6	3.41	1.33	4.00	23	DE6	3.75	1.00	3.50	15	-0.567	0.571

Recycling (GR) countries: BE, UK, FR, NL, DK. Non-recycling (NGR) countries: AU, DE, GR, SP, PT

4.1. Main differences between respondents in GR and NGR countries

Results from NGR countries were much more spread out (*SD* above 1 in most of the cases) than those from GR countries (SD below 1 in most of the cases). These differences could be attributed to the different level of information on GW management in NGR countries, which did not allow greater consensus between stakeholders. It is interesting to note that the least valued practices in GR countries coincide with highly variable opinions among stakeholders (see standard deviation, importance column, in Table 2). We refer to four practices: "Effective planning of GW capture systems" (DE8), "Address the end-of-waste (EoW) status" (GE1), "Availability of suitable closed-top skips" (GE2) and "Appointment of trained workers" (DE6). Fig. 1 and Fig. 2 provide further insight into this variability in terms of importance, showing that quite different perceptions exist between GR and NGR countries (Fig. 1) and stakeholders (Fig. 2).

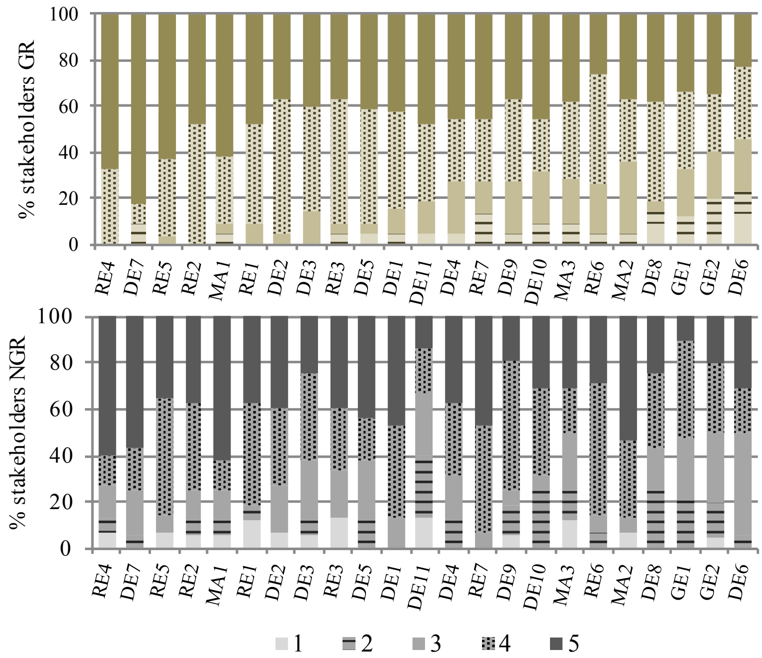

Fig. 1. Results of the questionnaire survey on the importance of practices. Recycling (GR) countries: BE, UK, FR, NL, DK. Non-recycling (NGR) countries: AU, DE, GR, SP, PT

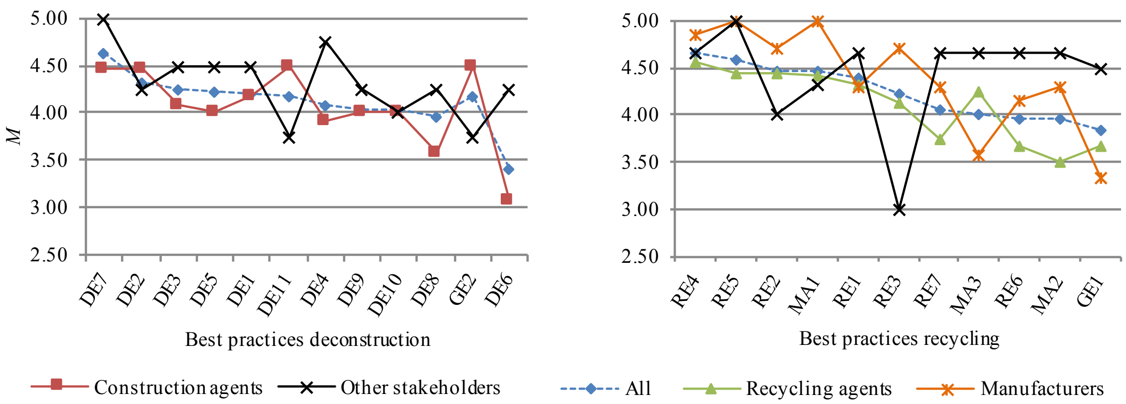

Fig. 1. Importance given by different stakeholders in GR countries (BE, UK, FR, NL, DK) and NGR countries 8 AU, DE, GR, SP, PT)

Only one practice, "Perform GW traceability, from source to final destination" (DE11), demonstrated a significant difference in terms of importance between GR (M=4.19, SD=1.03) and NGR countries (M=2.93, SD=1.28), as shown in Table 2. It is interesting to note that DE11 presents the higher proportion of respondents (40%) that scored it below 3 in NGR countries, which compares well with the results revealed by the Mann-Whitney U test. By contrast, 81% of GR stakeholders perceived traceability as highly or extremely important (see Fig. 1). This could be because traceability principles are not yet embraced by NGR countries and, therefore, NGR stakeholders are not familiar with tracking waste materials to the final destination. In addition, voluntary traceability tools and initiatives have already emerged in GR countries (e.g. Tracimat in Belgium or SmartWaste in the UK, as detailed in Section 2).

In the NGR stakeholders' responses, two practices are viewed as promising to improve the value chain: "Agree suitable supply contracts between recyclers and manufacturers" (RE7) and "Promote plasterboard take-back schemes" (MA2), which ranked first and third respectively (while for GR countries, these practices ranked 16 and 19 respectively, see Table 2 for further details). With regard to MA2, these results may indicate that stakeholders in NGR countries rely on the concept of the extended producer responsibility in order to enhance gypsum waste management. The reason for the score of RE7 in NGR countries may have something to do with the lack of nearby gypsum recyclers in these countries and therefore the impossibility of agreeing such contracts.

4.2. *Proposed fundamental best practices to enable a circular economy for gypsum products*

Three best practices are identified as fundamental (see Section 3 for details on the application of the criteria) to promote a circular economy for gypsum products: "Set clear waste acceptance criteria" (RE4), "Perform on-site segregation of GW" (DE7) and "Set clear RG quality criteria" (MA1).

4.2.1. Set clear waste acceptance criteria

"Set clear waste acceptance criteria" (RE4) was the highest rated practice in terms of importance for an efficient closed-loop supply chain (Table 2). This high score can be explained by the decisive role of these criteria on the accept or reject decision by the recycler. Moreover, stakeholders should follow such criteria in order to adequately collect (e.g. on-site collection, performed by construction agents) and supply (e.g. waste collectors, transfer stations) the waste. This practice is considered to be extremely important (i.e. score of five) by around 60% of respondents in both groups of countries. Surprisingly, recycling agents rated RE4 below the average ($M=4.56$; $SD=0.53$). This may be due to the confidence of recyclers on their current waste acceptance criteria, along with the appointment of skilled workers to perform hand-sorting at the recycling plant. As can be observed in Fig. 3, RE4 is implemented in 80% of the cases in GR countries ($M=4.00$; $SD=1.11$), while it is not a usual practice in NGR ones ($M=2.23$; $SD=1.42$, see Table A.1. in Appendix A for further details). This practice demonstrates a statistically significant difference between both group of countries in terms of implementation ($Z=-3.29$; $p=0.001$) and feasibility ($Z=-4.23$; $p=0.000$).

4.2.2. Perform on-site segregation of gypsum waste

"Perform on-site segregation of GW" (DE7) ranked second ($M=4.64$; $SD=0.90$) in GR countries (see Table 2). This practice is considered to be extremely important by 82% of respondents in GR countries (Fig. 1). In these GR countries, construction agents valued this segregation below the rest of stakeholders ($M=4.46$; $SD=1.13$). One possible explanation is that construction agents rely on subsequent segregation in a transfer station. As Wang et al. (2010) found, factors such as cost considerations or managerial issues might impact their response. However, mixed waste collection on-site does not benefit the recyclability of the gypsum fraction. In terms of implementation, while 78% commonly applied DE7 in GR countries, only 50% implement it in NGR countries (Fig. 3). This percentage compares well with the value obtained by Villoria Saez et al. in a survey conducted in 2012 in Spain (NGR country), in which 43% of construction agents did not claim to practice source separation. As a result, the segregated GW is consequently landfilled in NGR countries, as there are no gypsum recyclers nearby. The mean value obtained for implementation in these NGR countries ($M=3.06$; $SD=1.24$) compares well with the value obtained by Lu and Yuan in the survey conducted in Shenzhen (China) in 2008 ($M=3.00$; $SD=0.62$). This segregation of gypsum is usually performed in order to avoid contamination of concrete (Barbudo et al., 2012; Silva et al., 2014; Tovar-Rodríguez et al., 2013), and represents a lost opportunity to produce recycled gypsum. While more than 80% of respondents in GR countries perceived this on-site segregation as feasible ($M=4.64$; $SD=0.90$), only 56% agreed with this in NGR countries ($M=3.13$; $SD=1.45$) (Fig. 3 and Table A.1. in Appendix A). This can be explained by the deep-rooted tradition of on-site mixed waste collection in these contexts, which produce a significant difference between countries regarding the implementation ($Z=-2.84$; $p=0.005$) and feasibility ($Z=-4.00$; $p=0.000$) of DE7.

4.2.3. Set clear recycled gypsum quality criteria

"Set clear RG quality criteria" (MA1) ranked fifth in both group of countries (Table 2) and is regarded as extremely important by around 60% of stakeholders in both group of countries (Fig. 1). Interestingly, all manufacturers in GR countries considered MA1 as extremely important, which compares well with the increasing interest of developing quality criteria documents in countries such as Germany and the UK, as well as the European guidelines produced within the GtoG project (Bundesverband der Gipsindustrie e.V., 2013; GtoG project, 2015b; WRAP and BSI, 2013). The Mann-Whitney U test revealed a significant difference between GR and NGR respondents with regard to the implementation of MA1 (Z=-2.86; p=0.004).

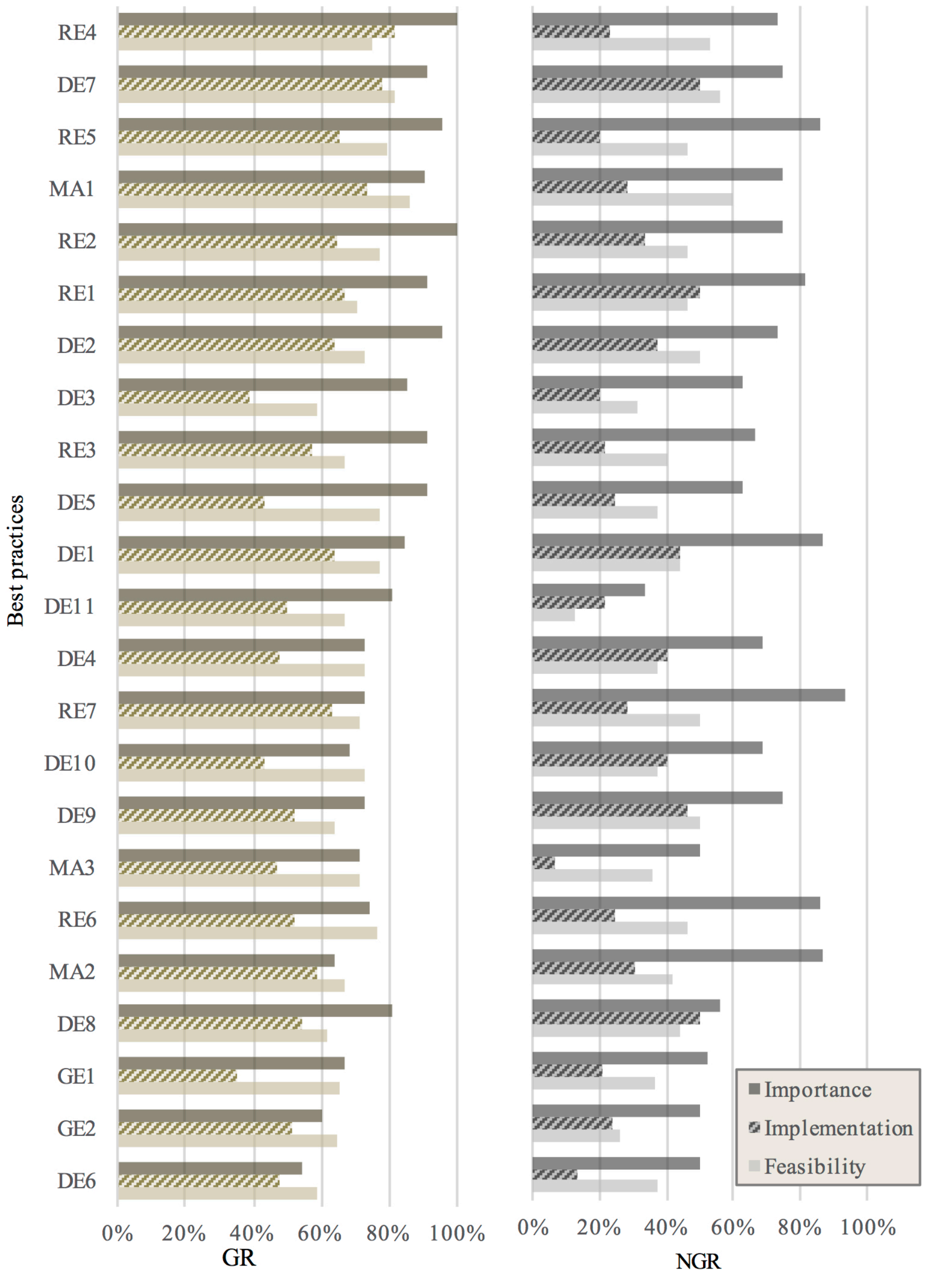

Fig. 2. Rate of respondents that highly implement the practice (I) and perceive it as highly feasible (F), above 4 in the rating scale. Recycling (GR) countries: BE, UK, FR, NL, DK. Non-recycling (NGR) countries: AU, DE, GR, SP, PT.

5. Conclusions

Once end-of-life (EoL) construction products are generated, adopted practices by stakeholders play a central role in determining their fate. Best practices on waste management, if properly organized and implemented, benefit the waste hierarchy and promote a circular economy of products, which prevents losses of potential secondary raw materials. In this investigation, we have proposed a set of best practices for the management of EoL gypsum in a circular economy. Moreover, we have examined how the best practices are viewed by stakeholders working in gypsum recycling (GR) and non-recycling (NGR) countries. The survey conducted targeted European stakeholders of the deconstruction-recycling value chain.

Three best practices are identified as fundamental to enable a circular economy for gypsum products: "Perform an on-site segregation of gypsum waste", "Set clear waste acceptance criteria" and "Set clear RG quality criteria". At present, on-site segregation of gypsum waste is only commonly applied by half of stakeholders in NGR countries (mainly to avoid EoL concrete contamination, then gypsum waste ends up in landfills due to the lack of gypsum recycling plants in NGR countries). This on-site segregation of gypsum waste enhances the generation of recyclable gypsum waste (i.e. in compliance with the waste acceptance criteria) and thus the production of recycled gypsum that complies with the agreed recycled gypsum quality criteria. Once these fundamental practices are in place in a region, the rest of best practices aim to provide guidance for stakeholders to enable informed decisions to be made regarding adopted practices during the EoL stage. Although this study focused on EoL gypsum in the European Union, the best practices here identified are valuable for replication in other regions and waste fractions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jclepro.2017.05.068.

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