Universidad Politécnica de Madrid
Escuela Técnica Superior de Edificación
Programa de Doctorado Innovación Tecnológica en Edificación

Gypsum Waste Management in the European Union: Towards a
Circular Economy for the Construction Sector

Tesis Doctoral

2016

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TESIS DOCTORAL

Título: “Gypsum Waste Management in the European Union: Towards a Circular Economy for the Construction Sector”

Tribunal nombrado por el Sr. Rector Magfco. de la Universidad Politécnica de Madrid, el día de de 2016.

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ABSTRACT

The role of waste management in the circular economy has recently been highlighted by the European Commission, particularly in the Communication COM/2015/0614 “Closing the loop – An EU action plan for the Circular Economy”. Gypsum products are well suited for contributing to this challenge, because the raw material calcium sulphate dihydrate can repeatedly change its properties through a reversible hydration reaction. Moreover, the waste hierarchy is applied when these are recycled instead of landfilled, which contributes to the European 2020 target of 70% recovery by weight of construction and demolition waste, as defined in the Directive 2008/98/EC on Waste. Three main undesirable effects are produced when gypsum is not managed appropriately, mainly due to its non-inert nature and its high sulphate content. On the one hand, gypsum contaminates concrete waste for recycling when treated as mixed waste. On the other hand, the disposal of gypsum waste at landfills poses a risk of higher landfill emissions. Overall, potential secondary resources are lost (i.e. recycled gypsum).

The main objective of the thesis is to broaden the knowledge on the management of gypsum products in the European Union, with the ultimate aim to move towards higher recovery rates and a closed-loop supply chain. This is intended to foster the transition to a circular economy and contribute to meet the European 2020 targets. The method includes the study of the literature, the development of a life cycle model and the design and analysis of questionnaires addressed to stakeholders. The investigation is partly based on 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”, supported by the European Commission through the Life+ programme (LIFE11 ENV/BE/001039).

On this basis, the investigation is tackled on two fronts: at macro and micro-levels. At macro-level, the results show how gypsum waste is managed in different European countries and the crucial factors that affect its destination. Additionally, the life cycle model of gypsum mass flows enables the estimation of primary energy use and greenhouse gases emissions in different recycling scenarios. Results reveal that such emissions are lower as recycling increases, largely driven by the degradation of plasterboard lining paper in landfill. At micro-level, the ideal conditions to produce quality recycled gypsum from end-of-life gypsum are formulated. Moreover, the physical and mechanical characterization of recycled gypsum and plasterboard with recycled content are examined. The identification of best practices for the management of end-of-life gypsum complements this part, being three practices proposed as fundamental to promote a circular economy for gypsum products. This study thus provides a comprehensive approach on measures to transform the management of gypsum waste in countries where gypsum is currently landfilled.

Overall, the study addresses six specific objectives, which are formulated as follows: (1) Document the current situation on the recycled gypsum market, (2) Evaluate the impact of different levels of gypsum recycling and landfilling, (3) Analyse the factors influencing gypsum recycling, (4) Analyse the characterization of gypsum feedstock and gypsum products with recycled gypsum, (5) Identify the ideal

conditions to produce recycled gypsum from end-of-life gypsum (6) Analyse practices for the management of end-of-life gypsum in a circular economy. The overall conclusion is that closed-loop gypsum recycling rates are influenced by factors (at a regional, national and EU level) and adopted practices by agents (in each deconstruction-recycling value chain). The lessons learned from current gypsum recycling countries have the potential to enable a circular economy in the rest of the European countries.

RESUMEN

La Comisión Europea ha señalado recientemente el papel de la gestión de residuos en la economía circular en la Comunicación COM/2015/0614 “Cerrar el círculo: un plan de acción de la UE para la economía circular”. Los productos de yeso son idóneos para contribuir a este reto, ya que el sulfato de calcio dihidratado puede cambiar repetidamente sus propiedades debido al proceso reversible de hidratación. Además, tal y como se define en la Directiva 2008/98/CE, la jerarquía de residuos se hace efectiva cuando los productos de yeso son reciclados en lugar de ser depositados en vertederos, lo que contribuye a alcanzar el objetivo europeo en 2020, relativo a la recuperación del 70% en peso de los residuos de construcción y demolición. Cuando los residuos de yeso no son gestionados adecuadamente se producen tres efectos indeseables. Por un lado, en caso de ser tratados como residuos mixtos, el yeso contamina los residuos de hormigón destinados a ser reciclados. Por otra parte, la disposición de residuos de yeso en vertedero representa un riesgo de mayores. En general, se pierden potenciales recursos secundarios (i.e. yeso reciclado).

Es principal objetivo de la tesis el ampliar el conocimiento en torno a la gestión de los residuos de yeso en la Unión Europea, con el fin último de evolucionar hacia mayores porcentajes de recuperación y una cadena de suministro de ciclo cerrado. Se pretende así fomentar la transición hacia una economía circular y contribuir a alcanzar los objetivos europeos en 2020. La metodología incluye el análisis de la bibliografía, el desarrollo de un modelo de ciclo de vida y el diseño y análisis de encuestas dirigidas a los agentes implicados. La investigación se basa en parte en el proyecto europeo *Life+ Gypsum to Gypsum (GtoG) project “From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry”*, supported by the European Commission through the *Life+ programme* (LIFE11 ENV/BE/001039).

Sobre esta base la investigación se aborda en dos frentes. A una escala más amplia, los resultados muestran cómo distintos países de la Unión Europea gestionan los residuos de yeso y los factores cruciales que afectan a su destino. De manera adicional, el modelo de ciclo de vida basado en los flujos de masas permite estimar la energía primaria y gases de efecto invernadero en distintos escenarios de reciclado. Los resultados muestran que estas emisiones son menores a medida que el reciclado aumenta, lo que se atribuye en gran medida a la degradación en vertedero del papel que forma parte de las placas de yeso laminado. A pequeña escala, se formulan las condiciones ideales para producir yeso reciclado de calidad procedente de residuos de yeso en la etapa de fin de vida. Además, se analiza la caracterización física y mecánica de residuo de yeso y producto con contenido reciclado. Lo anterior se complementa con la identificación de las mejores prácticas para la gestión de residuos de yeso en la etapa de fin de vida, proponiendo tres de ellas como fundamentales para promover una economía circular para los productos de yeso. El estudio proporciona así un enfoque amplio para transformar la gestión de los residuos de yeso en contextos en los que actualmente es dispuesto en vertedero.

En líneas generales, el estudio aborda seis objetivos específicos, formulados como sigue: (1) Documentar la situación actual en relación con el mercado de yeso reciclado, (2) Evaluar el impacto de distintos niveles de reciclado y eliminación en vertedero de yeso, (3) Analizar los factores que influyen en el reciclado del yeso, (4) Analizar la caracterización del yeso y productos de yeso con contenido reciclado, (5) Identificar las condiciones ideales para producir yeso reciclado a partir de productos de yeso al final de su vida útil, (6) Analizar prácticas para la gestión del residuo en una economía circular. Como conclusión general puede señalarse que las tasas de reciclaje de yeso se ven influenciadas por factores (a nivel regional, nacional y europeo) y prácticas adoptadas por los agentes (en cada cadena de suministro de construcción-reciclado). Las enseñanzas extraídas de países que actualmente reciclan yeso pueden hacer posible una economía circular para los productos de yeso en el resto de países europeos.

MAIN ABBREVIATIONS

BAU	Business-as-usual
BPI	Best practice indicator
C&D waste	Construction and demolition waste
CF	Critical factor
CH ₄	Methane
CO ₂ eq	Carbon dioxide equivalent
EoL	End-of-life
EoW	End-of-waste
FGD	Flue gas desulfurization
GHG	Greenhouse gas
GR country	Gypsum recycling country
GW	Gypsum waste
H ₂ S	Hydrogen sulphide
KPI	Key performance indicator
LCI	Life cycle inventory
M	Mean value
Mt	Million tonne
NGR country	Non-gypsum recycling country
RG	Recycled gypsum
SD	Standard deviation
SWMP	Site waste management plan
TOC	Total organic carbon
WAC	Waste acceptance criteria

PART I: GENERAL INTRODUCTION

GENERAL INTRODUCTION

Background

The Directive 2008/98/EC on waste establishes a recovery target of 70% by weight by 2020 on construction and demolition waste (C&D waste), which is still far to be met (European Parliament and the Council of the European Union, 2008). The target excludes hazardous C&D waste and naturally occurring material (i.e. excavated material). Diverse estimations on the total weight annually generated can be found in the published literature, mainly depending on whether naturally occurring materials are considered. Figures typically vary between 500¹ and 800² million tonnes of waste per year in the European Union, of which only 46% were estimated to be re-used or recycled in 2008 (European Commission (DG ENV), 2011).

Aside from this, the European Commission is establishing the framework of a transition from a linear to a more circular economy (European Commission, 2014a, 2015a, 2015b), which is one of the core concepts of increasing resource efficiency (European Parliament, 2015). In a circular economy, “resources that would otherwise become wastes” are returned “back into the economy” (Velis, 2015), thus closing the material loop. A recent Communication from the Commission introduced an action plan at EU level for all waste streams, being C&D considered as a priority area³ (European Commission, 2015a). A circular economy requires action at each life cycle stage, such as product design, production processes, consumption and waste management. The latter has an important role to play in the destination of end-of-life products (i.e. re-use, recycling, recovering or landfilling), particularly for those construction products which are already part of the buildings and for which strategies in the other mentioned stages are no longer applicable.

Different C&D waste streams can be distinguished by their nature. The case of gypsum waste (GW), a non-inert material, is found to be quite particular, as its reversible hydration chemical process makes it indefinitely recyclable (Eurogypsum, 2006) and thus well-suited for closing the loop in a circular economy. In 2011, the gypsum industry estimated that GW made up around 1% of the total C&D waste (GtoG project, 2013a). Although this is quite a small percentage, diverse undesirable effects are

¹ Based on a calculation performed by European Commission (DG ENV) (2011), excavated material excluded, for the year 2008, which resulted in 531 million tonnes assuming a worst case scenario or figures from 2009 in countries in which data was not available. Calculations based on data from European Topic Centre on Resource and Waste Management and Umweltbundesamt.

² Eurostat (2012a), total non-hazardous, code F: construction: 805.1 million tonnes.

³ Other priority areas include plastics, food waste, critical raw materials and biomass and bio-based products (European Commission, 2015a).

produced when GW is not adequately managed, including the contamination of concrete for recycling (Barbudo et al., 2012) or the decomposition of gypsum to hydrogen sulphide in landfills (Gypsum Association, 1992). However, only between 5 and 10 per cent of the GW generated during the installation of gypsum plasterboard (i.e. construction waste) were estimated to close the loop in 2011 according to Eurogypsum (European Commission (DG ENV), 2011). The management of end-of-life gypsum products (or demolition waste) was considered to be more complex to address (compared to construction waste) because they might be attached to other building materials (GtoG project, 2013b).

Taking all this into consideration, 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, 2013a) was launched in 2013. Since then, the GtoG project has been working to transform the waste market of end-of-life gypsum, in order to achieve higher gypsum recycling rates and a more resource efficient economy. The participating consortium was coordinated by Eurogypsum, the European federation of national associations of gypsum products manufacturers, and consisted of 17 partners (two universities, five demolition companies, one consultant in deconstruction, five gypsum manufacturers, one laboratory and two gypsum recyclers) from seven European countries.

Gypsum products

Gypsum products are mainly composed of calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Examples include gypsum plasterboard and gypsum blocks (Fig.1). The hydration reaction of the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ is reversible (see Fig.2) and because of this, the material can repeatedly change its properties, which enables closing the material loop. Closing the gypsum loop in a circular economy involves collecting and managing gypsum products once they do not provide any further functionality (European Commission, 2015; CEN, 2013), with the aim to obtain recycled gypsum and reincorporate it into the manufacturing of new gypsum products.

Fig.1. Plasterboard (left) and gypsum blocks (right). Source: GtoG project (2013b) and Müller (2010)

Fig.2. Basics of gypsum processing to be a product ready for use. Updated version of the one prepared for the Current Practices report (GtoG project, 2013b). Original source: (Eurogypsum, 2008)

This thesis focuses on gypsum recycling into new gypsum products (also referred to as “closing the loop of gypsum” or “closed-loop gypsum recycling”). It should be noted that, apart from the gypsum industry, other sectors also use gypsum. While the cement industry uses gypsum as a set retarder in Portland cement (Chandara et al., 2009), the agriculture sector uses it mainly because of its calcium and sulphur content (Jang & Townsend, 2001; Summer, 1995). Other applications include dentistry, food additives and moulding (Roskill, 2014). However, closing the loop of gypsum maximizes the chances of subsequent gypsum recycling.

Examples of gypsum products consumed are first presented in Chapter 2, Section “Type of gypsum waste”. Most of these products are plasterboard, along with small quantities of gypsum blocks or other plaster products (e.g. plaster ceilings). As this chapter reveals, around 81% of the total consumed in 2012 in the EU-27 corresponded to plasterboard, which indicates the type of end-of-life (EoL) gypsum that will be generated at the end of their service lives.

This investigation addresses all types of recyclable GW. However, in those chapters based on data from the GtoG case studies (i.e. Chapters 5, 6 and 7) the main focus remains on plasterboard as it is the main EoL product generated. Gypsum blocks were generated in a case study in France (Pilot project “PII” in Chapter 5). Nevertheless, the best practices formulated in Chapter 6 are applicable to all GW.

Landfill of gypsum waste versus gypsum recycling

Different types of GW are distinguished based on the source of the product, the main difference of which is the amount of impurities and moisture that are present. Pre-consumer is already typically recycled in most national contexts (see Chapter 2), being part of the manufacturers’ waste avoidance corporate

policy. However, limited quantities of post-consumer GW is currently diverted from landfills (see Chapter 3).

At present, two different routes for gypsum waste can be distinguished: the disposal route and the recycling route (Fig.3). The recycling route of post-consumer GW typically involves sorting on-site, collection and transport from the site to the recycling facility and processing. Known benefits of recycling include resource efficiency and prevention of land occupation. The landfill route commonly implies mixed collection and transport from the site to the landfill. This is further detailed and quantified through distinct recycling scenarios in Chapter 2 and Appendix 1.

Fig.3. Different disposal and recovery routes for gypsum waste based on GtoG project (2013b) and WRAP (2008)

From gypsum waste to recycled gypsum

GW is processed into RG through a series of mechanical steps such as crushing (i.e. to convert different sizes of waste into gypsum powder) and sieving (i.e. to separate paper waste or potential impurities from the recycled gypsum). Three main business models are identified across Europe (GtoG project, 2013b):

- Fixed recycling units annexed to plasterboard manufacturing plants.
- Mobile recycling units collecting GW from different locations and processing the waste in a recycling facility closely located to plasterboard manufacturing plants.
- Plasterboard manufacturers that own a fixed recycling unit for processing post-consumer GW.

Accordingly, diverse recycling systems exist, which differ in parameters such as mobility or capacity. Two examples of patented technology are shown in and Fig.4 and Fig.5. While Fig.4 presents a mobile unit, Fig.5 depicts a fixed machine. Both recycling units are currently in operation in the European Union.

Fig.4. Example of fixed gypsum recycling equipment. Source: Method and apparatus for separating adhered paper from paper-covered gypsum board. Patent Pub. N.: US 2003/0189116 A1. United States Patent Application Publication. Separation apparatus 10H. 12: feed hopper; 14: conveyor; 22: presorting belt, where non-gypsum material is manually sorted out and removed; 28: self-cleaning belt; 30: ferrous materials; 16: magnet; 18: pulverized; 20: screen to segregate pieces of paper and gypsum; 24: screen where the material is further segregated; 32: self-cleaning belt; 34: finer ferrous materials; 26: second magnet (McCamley, 2003).

Fig.5. Example of mobile gypsum recycling equipment (the apparatus is arranged on a trailer for road transportation: 24). Source: Recycling apparatus for gypsum plasterboards. Patent EP1421995 A1. European Patent Application. 25: power pack; 2: hopper; 3: crusher; 4: magnetic separator; 26: first conveying means; 14: roller mill; 27: separating drum; 22: vacuum installation; 28: paper press; 16: conveyor; 29: openings to chutes (Rasmussen, 2004).

Post-consumer GW from all sources (e.g. deconstruction, renovation, construction, see column “Source” in Fig.6) should comply with the waste acceptance criteria (WAC) of the recycler (see Chapter 5) in order to be recyclable. Two main aspects can convert recyclable GW waste into a non-recoverable material: impurities and moisture. The main sources of GW per country are examined in Chapter 1 “Gypsum waste generation and management”.

Fig.6. From gypsum waste to recycled gypsum. The estimated weight percentage was calculated using data from the Report on Current Practices GtoG project (2013b). GW: gypsum waste, C&D: construction and demolition, RG: recycled gypsum.

In this study, particular attention is paid to the EoL processes (part of EoL stage) and the resulting EoL gypsum products, mainly for two reasons. First, waste generated in this stage cannot be reduced by means of alternative strategies (e.g. minimization of waste during installation of the gypsum system). Second, most EoL gypsum products are currently landfilled because of a number of conditions that needed to be studied (e.g. practices in this stage as presented in Chapter 5 “End-of-life case studies analysis” and Chapter 6 “Best practices in the end-of-life stage”).

Problem statement

- Although calcium sulphate dihydrate is recyclable and the technology for gypsum recycling exists, most post-consumer gypsum waste is landfilled in Europe (European Commission (DG ENV), 2011).
- When gypsum products are landfilled in mixed waste landfills, there is a risk of higher greenhouse gas and hydrogen sulphide emissions (WRAP, 2008). Although monocell landfills as defined in the Council Decision 2003/33/EC can mitigate the problem, these dedicated cells are still limited (GtoG project, 2013b).
- Non-separate collection of GW and landfilling often means contamination of EoL concrete (Barbudo et al., 2012) and sulphate leaching potential risk (Jang & Townsend, 2001; Sun & Barlaz, 2015).

Main objective and specific objectives of the thesis

Closely related to the problem statement, the main objective of this thesis is to broaden the knowledge on the management of gypsum products in the European Union, with the aim to move towards higher recycling rates and a closed-loop supply chain. To accomplish this purpose, six specific objectives are tackled.

These specific objectives are categorized into two complementary levels: macro and micro-level. At macro-level, the overall situation on gypsum recycling and landfilling is studied (Chapter 1, Chapter 2 and Chapter 3). At micro-level, 3 chapters focus on the analysis of the deconstruction-recycling value chain and the role of stakeholders on it. On the one hand, Chapter 4 and Chapter 5 benefit from data collected from the GtoG case studies. On the other hand, based on the knowledge gained from the rest of chapters, Chapter 6 outlines best practices for an improved deconstruction-recycling value chain.

At macro-level:

- O1. Document the current situation on the recycled gypsum market (Chapter 1).
 - O1.1. Document the type and source of gypsum products consumed and gypsum waste recycled.
 - O1.2. Document the recycled gypsum quality criteria of the European gypsum manufacturers.
- O2. Evaluate the impact of different levels of gypsum plasterboard recycling and landfilling (Chapter 2).
- O3. Analyse the factors influencing gypsum recycling and landfilling (Chapter 3)

At micro-level:

- O4. Analyse the characterization of gypsum feedstock and gypsum products with recycled gypsum (Chapter 4)
- O5. Identify the ideal conditions to produce recycled gypsum from end-of-life gypsum (Chapter 5)
- O6. Analyse practices for the management of end-of-life gypsum in a circular economy (Chapter 6)

Main research questions

The specific objectives of the thesis have been also expressed in the form of research questions. These questions motivated this thesis and provide continuity between the various chapters. Aiming to ease the reading of the document, a brief answer to each question is provided at the beginning of each chapter.

- What is the main type of gypsum product consumed in the EU? (O1.1, Chapter 1)
- What type of gypsum waste is currently recycled in the EU? (O1.1, Chapter 1)
- What are the existing specifications for recycled gypsum in the EU? (O1.2, Chapter 1)

- How do different levels of gypsum recycling correlate with the primary energy use and the GHG emissions of the plasterboard life cycle in the EU? (O2, Chapter 2)
- What factors influence gypsum recycling in the EU? (e.g. why does a market for recycled gypsum exist in gypsum-recycling countries but not yet in other national contexts?) (O3, Chapter 3)
- How does recycled gypsum with increased recycled content compare with business-as-usual gypsum feedstock? (O4, Chapter 4)
- What conditions should be met during deconstruction and processing of gypsum waste to produce quality recycled gypsum (O5, Chapter 5)
- What practices adopted by stakeholders affect gypsum waste management? (O6, Chapter 6)

Outline of the thesis

The thesis consists of six chapters and four parts as shown in Fig.7. Each chapter is based on a journal article (published, accepted for publication or under review).

Fig.7. Overview of the chapters and the related articles

Information on the journals and conference in Fig. 7 is provided below. It should be noted that the information on the impact factor refers to the reference year 2015.

- International Journal of Sustainability Policy and Practice. Subject Area: Energy, Environmental Science, Social Sciences. Publisher: Common Ground Publishing. ISSN: 23251182, 23251166. SJR indicator (SCOPUS): 0.118.
- Journal of Cleaner Production. Business, Management and Accounting, Energy, Engineering, Environmental Science. Publisher: Elsevier BV. SJR indicator (SCOPUS): 1.721. JCR: 4.959 (Q1).
- Materiales de Construcción. Subject Area: Engineering, Materials Science. Publisher: Instituto de Ciencias de la Construcción Eduardo Torroja. ISSN: 04652746. SJR indicator (SCOPUS): 0.523. JCR: 0.96 (Q3).
- Resources, Conservation and Recycling. Subject Area: Economics, Econometrics and Finance, Environmental Science. Publisher: Elsevier BV. ISSN: 09213449. SJR indicator (SCOPUS): 1.36. JCR: 3.28 (Q1, Environmental Sciences; Q2, Engineering, Environmental).
- SGEM2015 Conference. 15th International Multidisciplinary Scientific GeoConferences. Area: Energy and Clean Technologies. Subject Area: Energy & Fuels; Geology; Nuclear Science & Technology. ISSN: 1314-2704. Conference proceedings indexed by Web of Science and SCOPUS.
- Waste and Biomass Valorization. Subject Area: Energy, Environmental Science. Publisher: Springer Verlag. ISSN: 1877265X, 18772641. SJR indicator (SCOPUS): 0.411. JCR: 0.915 (Q4).

References

- Barbudo, A., Galvín, A. P., Agrela, F., Ayuso, J., & Jiménez, J. R. (2012). Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes. *Waste Management*, 32(6), 1229–35.
<http://doi.org/10.1016/j.wasman.2012.02.005>
- Chandara, C., Azizli, K. A. M., Ahmad, Z. A., & Sakai, E. (2009). Use of waste gypsum to replace natural gypsum as set retarders in portland cement. *Waste Management*, 29(5), 1675–9.
<http://doi.org/10.1016/j.wasman.2008.11.014>
- Eurogypsum. (2006). Plaster and Plasterboard. The sustainable construction materials for the 21st century. 1. Drywall Systems - Sound investment that adds to Home Value - GPDA.
- Eurogypsum. (2008). Living with Gypsum : From Raw Material to Finished Products.
- European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Towards a circular economy: A zero waste programme for Europe (2014).
- European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy (2015a). Retrieved from http://ec.europa.eu/environment/circular-economy/index_en.htm
- European Commission. (2015b). Roadmap Circular Economy Strategy. Retrieved from http://ec.europa.eu/smart-regulation/impact/planned_ia/docs/2015_env_065_env+_032_circular_economy_en.pdf

- European Commission (DG ENV). (2011). Service Contract on Management of Construction and Demolition Waste - SR1. Final Report Task 2. A project under the Framework contract ENV.G.4/FRA/2008/0112. Retrieved 17 January 2016, from http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf
- European Committee for Standardization (CEN). EN 15804:2012+A1:2013. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (2013).
- European Parliament. Committee on the Environment, P. H. and F. S. (2015). Draft report on resource efficiency: moving towards a circular economy 2014/2208(INI).
- European Parliament and the Council of the European Union. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Retrieved 12 April 2015, from <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:en:PDF>
- Eurostat. (2012). Generation of waste, NACE Rev. 2. Code F, Construction. Non-hazardous. 2012. Last update: 23-07-2015.
- GtoG project. (2013a). Life+ Gypsum to Gypsum (GtoG) project 'From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry' LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4191
- GtoG project. (2013b). DA1: Inventory of current practices LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from <http://gypsumtogypsum.org/documents/deliverable-a1-report-on-current-practices.pdf>
- Gypsum Association. (1992). Treatment and disposal of Gypsum Board Waste. Washington, D.C. Retrieved 28 September 2014, from http://www.awci.org/cd/pdfs/9202_a.pdf
- Jang, Y.-C., & Townsend, T. (2001). Sulfate leaching from recovered construction and demolition debris fines. *Advances in Environmental Research*, 5(3), 203–217. [http://doi.org/10.1016/S1093-0191\(00\)00056-3](http://doi.org/10.1016/S1093-0191(00)00056-3)
- McCamley, J. A. (2003). Method and apparatus for separating adhered paper from paper-covered gypsum board. United States Patent Application Publication.
- Müller, A. (2010). Gypsum in C&D aggregates – Origin, Effects, [Separation] and Utilization. In Bauhaus-Universität Weimar.
- Rasmussen, K. (2004). Recycling apparatus for gypsum plasterboard. European Patent Application.
- Roskill. (2014). Gypsum and Anhydrite: Global Industry Markets and Outlook (Eleventh).
- Summer, M. E. (1995). Literature review on gypsum as a calcium and sulfur source for crops and soils in the southeastern United States. Publication No. 01-118-118.
- Sun, W., & Barlaz, M. a. (2015). Measurement of chemical leaching potential of sulfate from landfill disposed sulfate containing wastes. *Waste Management*, 36, 191–196. <http://doi.org/10.1016/j.wasman.2014.11.014>
- Velis, C. A. (2015). Circular economy and global secondary material supply chains. Editorial. *Waste Management & Research*, 33(5), 389–391. <http://doi.org/10.1177/0734242X15587641>
- WRAP and Environmental Resources Management Ltd (ERM). (2008). Technical Report: Life Cycle Assessment of Plasterboard.

PART II: MACRO-LEVEL

1 GYPSUM WASTE GENERATION AND MANAGEMENT

CHAPTER OVERVIEW

This chapter focuses on the analysis of a European survey conducted and consolidated by Eurogypsum between 2012 and 2013. The survey explored differences on the gypsum waste generation and management in 10 European countries. Moreover, the existing specifications for recycled gypsum (RG quality criteria) were documented. In a complementary manner, this chapter explores the type of gypsum products consumed in the European Union, based on data from the European database Prodcorn. Such current consumption patterns anticipates the future patterns of generation of end-of-life (EoL) gypsum.

Published as

Jiménez Rivero, A., de Guzmán Báez, A., & García Navarro, J. (2015). Gypsum Waste: Differences across Ten European Countries. *The International Journal of Sustainability Policy and Practice*, 11(4), 1–9.

Main research questions addressed and relation to other chapters

	Research question (and related specific objective in parentheses)	Brief answer and → Relation with other chapters
<div> <div>Chapter 1. Gypsum waste generation and management</div> <div>Chapter 2. Life cycle energy and material flows</div> <div>Chapter 3. Factors influencing post-consumer gypsum recycling</div> <div>PART II: MACRO-LEVEL</div> </div>	i. What is the main type of gypsum product consumed in the EU? (O1.1)	i. Plasterboard makes up the majority of the gypsum products consumed → This is one of the reasons why Chapter 2 focuses on the life cycle of this gypsum product. Moreover, most of the analysis in Part III relates to plasterboard, as it is the main type of gypsum waste (GW) generated in the GtoG pilot projects.
	ii. What type of gypsum waste is currently recycled in the EU? (O1.1)	ii. Pre-consumer GW is commonly recycled. However, only half of the studied countries recycle post-consumer GW → In light of this finding, Chapter 2 analyses varying post-consumer GW recycling. In addition, Chapter 3 explores factors influencing the success of post-consumer gypsum recycling.
<div> <div>Chapter 4. Physical and mechanical characterization</div> <div>Chapter 5. End-of-life case studies analysis</div> <div>Chapter 6. Best practices in the end-of-life stage</div> <div>PART III. MICRO-LEVEL</div> </div>	iii. What are the existing specifications for recycled gypsum in the EU? (O1.2)	iii. Five distinct Quality Criteria for Recycled Gypsum are found in the EU. Based on this finding, the GtoG project worked to reach harmonised voluntary guidelines at EU level → Such guidelines are the basis of Chapter 4.

1.1. Introduction

Construction and Demolition (C&D) waste comprises different materials such as concrete, ceramics, wood, glass, plastic, metal and gypsum products, as described in the European list of wastes - ELW (The Commission of the European Communities, 2000). Landfilling of these wastes contribute to environmental deterioration, while waste re-use, recycle and recovery slow down extensive resource consumption.

Gypsum products' main constituent is calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), coming from natural, synthetic or recycled sources. Gypsum is fully recyclable, changing form based on a reversible hydration reaction. However, a large proportion of gypsum waste is still being landfilled worldwide (European Commission (DG ENV), 2011), including building plaster, gypsum blocks and plasterboard, among others. The European Gypsum Industry is taking measures to reduce, re-use and recycle gypsum waste, therefore contributing to the 70% target for preparing for re-use, recycling and other material recovery of non-hazardous C&D waste by 2020, set down in Article 11(2) of the Directive 2008/98/EC, also known as Waste Framework Directive or WFD (European Parliament and the Council of the European Union, 2008). An example of collaborative approach to address this target is the Life+ Gypsum to Gypsum (GtoG) project "From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry", which from January 2013 is working to transform the gypsum waste market, with the aim of achieving higher gypsum recycling rates in Europe (GtoG project, 2013).

A circular economy system keeps the added value in products for as long as possible and reduces waste. This strategy of turning waste into a resource is an essential part of increasing resource efficiency and closing the loop in a circular economy (European Commission, 2014c). The plasterboard Industry closes the loop of plasterboard with the reincorporation of the recycled gypsum in the manufacturing of new plasterboard. Quality recycled gypsum requires proper management of gypsum waste, which commonly implies gypsum products dismantling and segregation of gypsum waste at source, in order to comply with the recyclers' acceptance criteria.

Closed-loop gypsum recycling preserves natural resources. Moreover, the contamination of recycled aggregates (Barbudo et al., 2012; Silva, de Brito, & Dhir, 2014; Tovar-Rodríguez, Barra, Pialarissi, Aponte, & Vázquez, 2013), sulfate leaching (Jang & Townsend, 2001; Sun & Barlaz, 2015), hydrogen sulfide (H_2S) generation (Lee et al., 2006; Xu & Townsend, 2014), methane (CH_4) and carbon dioxide (CO_2) emissions from landfills (WRAP and Environmental Resources Management Ltd (ERM), 2008) are prevented.

To our knowledge, no previous investigations have explored the current situation of gypsum waste management in the European Union. In this paper we present an overview on gypsum waste management in 10 European countries: Austria, Belgium, Germany, Denmark, France, Italy, the Netherlands, Spain, Poland and the United Kingdom. In addition, a brief overview of recycled gypsum quality criteria is provided. The objective is to introduce the peculiarities of this waste stream in the path

towards achieving a circular economy in the European Gypsum Industry, together with the Demolition and Recycling Industry.

1.2. Methodology

The current investigation involved a literature review on gypsum products use and gypsum waste generation. It consisted of an examination of journals, reports, databases and regulation impacting this fraction. Moreover, results from a questionnaire survey on gypsum waste management and recycled gypsum quality requirements were analyzed. The questionnaire was designed, distributed (in 2012) among gypsum manufacturers and consolidated by the European Plaster and Plasterboard Manufacturers Association (Eurogypsum). The survey focused on: type and source of gypsum waste, storage, recycling plants and recycled gypsum quality requirements⁴. It consisted of 9 closed questions (yes/no) and opened question for detailed description on the type of gypsum waste and recycled gypsum quality criteria limit values. Answers from Austria (AU), Belgium (BE), Germany (DE), Denmark (DK), France (FR), Italy (IT), Poland (PL), Spain (SP), the Netherlands (NL) and the United Kingdom (UK) were received. The consolidated results were made available to the GtoG project in January 2013, and were analyzed as part of a preliminary action.

Additionally, discussions with the stakeholders involved as well as site observations were conducted in the years 2013 and 2014 at various stages of the waste management process: deconstruction, gypsum waste reception and processing (recycling).

1.3. Results and discussion

1.3.1. *Type of gypsum products consumed and gypsum waste generated*

Gypsum waste generated is closely linked to gypsum products consumed. Thus, this section first explores gypsum products production and consumption in the European Union (EU-27). Gypsum blocks, plaster ceilings, decorative plaster and plasterboards are examples of recyclable gypsum products.

According to the indicator “Volume of production” (PRODQNT) in the Eurostat Prodcom Annual Sold database (NAVE Rev. 2, last update February 2015), for the EU-27 countries and for the period January to December 2012, the largest amount of recyclable gypsum products corresponds to plasterboard. Whereas the production of plaster materials faced with paper, code 23621050 (the case of plasterboard) accounts to 1,183 million m² in the EU-27, not faced plaster materials, code 23621090 (such as gypsum blocks, plaster ceilings, decorative plaster, glass reinforced gypsum products and molds) only amounts to 281 million m². Therefore, about 81% of the gypsum products currently manufactured in the EU-27 are plasterboard. Again, based on the Eurostat Prodcom database, the indicator “Apparent consumption” reflects the proportion of consumed gypsum products by adding the imports quantity to the production

⁴ Further information on the survey can be found in the GtoG deliverable DA1: Inventory of current practices (GtoG project, 2013b)

quantity, and subtracting the exports (Williams, 2008). No change resulted in the assessment of the proportion of faced and non-faced products in “Apparent consumption”, when compared to the “Volume of production” (about 81% corresponds to plasterboard). Fig. 1.1 presents the “Apparent consumption” per country and type of gypsum product consumed.

Fig. 1.1. Apparent consumption of faced (such as plasterboard) and not faced plaster products (such as gypsum blocks, plaster ceilings and decorative plaster). Not available PRODQNT for faced plaster materials: AU, BE, and PL. Not available PRODQNT for non-faced materials: BE, DE, PL and UK. *Source(s): Author's production based on Prodc database 2012 (Eurostat 2012)*

Moreover, Table 1.1 summarizes the type of gypsum products becoming gypsum waste that were identified by the interviewees from the different European countries. As can be seen, plasterboard is recycled in all countries under study and gypsum blocks are recycled in countries where they are consumed (Fig. 1.1).

Table 1.1. Type and source of gypsum waste and type of recycling facility. Examples of other in FR: plaster ceilings, powder and molds; DE: fibreboard; IT: plaster; NL: plaster; UK: plaster excluding base coat, ceiling tiles. Demolition comprises renovation, demolition and deconstruction works. * Isolated experiences, such as research projects. ** Not all the manufacturers *Source(s): Author's production based on results from the questionnaire survey*

	Type of gypsum waste			Source			Type of recycling facility	
	Plasterboard	Gypsum blocks	Other	Production	Construction	Demolition	Internal	External
AU	✓			✓	*		✓	
BE	✓	✓		✓	✓	✓		✓
DK	✓			✓	✓	✓	✓	✓
FR	✓	✓	✓	✓	✓	**	✓	✓
DE	✓	✓	✓	✓			✓	
IT	✓		✓	✓	*	*	✓	✓
PL	✓	✓		✓	*		✓	
SP	✓			✓	*		✓	
NL	✓	✓	✓	✓	✓	✓	✓	✓
UK	✓		✓	✓	✓	✓	✓	✓

It can be observed that the majority of the recyclable gypsum waste generated and recycled, both in the EU-27 and in each of the countries under study, corresponds to plasterboard waste.

1.3.2. Source of gypsum waste

Three different sources of gypsum waste can be distinguished: manufacturing plants, construction sites and renovation, demolition or deconstruction sites.

Gypsum waste generated during the manufacturing process is usually known as “production waste” or “pre-consumer production waste” and it is composed of out-of-specification boards (WRAP and Environmental Resources Management Ltd (ERM), 2008). The recycling of pre-consumer gypsum waste is part of the manufacturers’ waste avoidance corporate policy. In the framework of this study the resulting recycled gypsum is known as “pre-consumer recycled gypsum”. On the other hand, “post-consumer gypsum waste” is generated in construction, renovation, deconstruction or demolition works. Examples of post-consumer gypsum waste generated in construction works include damaged boards and offcuts. In all other cases post-consumer gypsum waste is composed of stripped-out gypsum products. The amount of recyclable post-consumer gypsum waste is maximized when gypsum products are dismantled and gypsum waste is segregated at source.

Gypsum products becoming gypsum waste that were identified by the interviewees from various European countries is presented in Table 1.1. Besides pre-consumer recycled gypsum, post-consumer recycled gypsum is being successfully reincorporated in the plasterboard manufacturing process in France, Belgium, Denmark, the Netherlands and the UK. Manufacturers in Italy, Spain and Poland are also incorporating a small amount of post-consumer recycled gypsum, however in most cases have resulted from isolated experiences or research projects, as no further evidences have been found so far.

1.3.3. Type of gypsum recycling facilities

Manufacturers usually process their own pre-consumer gypsum waste, but gypsum waste can also be processed externally by a third party, also known as gypsum recyclers, meaning individual or company that processes gypsum waste to produce recycled gypsum (WRAP and Environmental Resources Management Ltd (ERM) 2008). The questionnaire survey shows how most of the manufacturers that are currently reincorporating post-consumer recycled gypsum in their process are working with external recyclers apart from their own internal recycling plants. Except for Belgium, where only external recyclers are reported (Table 1.1).

Several mechanical steps, such as grinding and sieving, take place for processing the gypsum waste into recycled gypsum. In Europe, gypsum recyclers operate in France, Benelux (Belgium, the Netherlands and Luxembourg), Finland, the UK, Denmark, and Sweden.

1.3.4. European landfills for gypsum waste disposal

As gypsum is fully recyclable, only non-recyclable gypsum waste (due to contamination or non-appropriate dismantling practices) should ideally be landfilled.

High concentrations of H₂S at C&D waste landfills are attributed to H₂S generation from the disposal of gypsum plasterboard (CaSO₄·2H₂O) and consequent H₂S emissions (Xu & Townsend, 2014). If gypsum waste is accepted at normal cells in landfills, its sulphate would break down, among other substances, into H₂S, a hazardous flammable gas with negative environmental and health effects when inhaled, that even in small concentrations creates odour problems. CH₄ and carbon dioxide (CO₂) emissions are also generated when plasterboard is landfilled, caused by the degradation of the paper content (WRAP and Environmental Resources Management Ltd (ERM), 2008).

Strict separation of gypsum and biodegradable waste is already recommended in Section 2.2.3 of the Council Decision 2003/33/EC, which establishes that “non-hazardous gypsum-based materials should be disposed of in landfills for non-hazardous waste in cells where no biodegradable waste is accepted” (The Council of the European Union, 2003). One consequence of the correct implementation of this Commission Decision is the increase of the charges for disposing gypsum waste, as costs for operating monocells usually derive in additional costs. The later could increase the competitiveness of the recycling solution compared to local landfills, and thus promote gypsum recycling. In the framework of the GtoG Life+ project, evidence of monocell landfills operation is only found in Belgium, France and the UK.

More restrictive measures are found in Belgium and the Netherlands. Flanders (Belgium) implemented a ban on the disposal of unsorted waste (European Topic Centre on Sustainable Consumption and Production - EOINET, 2009). In addition, the Sectorial implementation plan D/2007/5024/70 (OVAM, 2007) already covered the idea of closing the loop of gypsum (European Topic Centre on Sustainable Consumption and Production - EOINET, 2009). In the Netherlands, a ban for sending recyclable materials to landfill exists (European Topic Centre on Sustainable Consumption and Production - EOINET, 2012; Fischer, Lehner, & Mckinnon, 2012).

1.3.5. Brief overview of recycled gypsum and end-of-waste (EoW) criteria

Recycled gypsum can be defined as “gypsum resulting from the controlled processing of waste plasterboard to separate the gypsum, paper lining, and any contaminants, such that it can be used in lieu of natural or synthetic gypsum” (WRAP and Environmental Resources Management Ltd (ERM), 2008). Two forms of recycled gypsum can be differentiated: pre-consumer recycled gypsum and post-consumer recycled gypsum. Its quality, especially when it is used in closed-loop recycling, is essential. Plasterboard manufacturers, when purchasing recycled gypsum, usually use contracts or agreements to specify the quality of the supplied recycled gypsum.

The GtoG project aims at obtaining the EoW status according to article 6 of the WFD, which would mean gypsum waste ceasing to be waste, laying down EoW criteria that provide a high level of environmental protection and an environmental and economic benefit (European Parliament and the Council of the European Union, 2008). The removal of the waste status can promote the production of higher quality secondary products by defining technical and environmental minimum requirements to be fulfilled by the materials. In addition, potential users of recycled gypsum that satisfies a set of EoW criteria should be able to have increased confidence on the quality standards of the material, thus helping

to alleviate any user prejudice against material simply because it is derived from waste (Delgado et al., 2009).

EoW criteria for the production and use of recycled gypsum from plasterboard waste are only a reality in the UK, governed by the Quality Protocol (WRAP & Environment Agency, 2013). In addition, PAS 109:2013 sets out the specification for the production of reprocessed gypsum (recycled gypsum or secondary material) from waste plasterboard (WRAP & BSI, 2013).

1.3.6. Quality criteria for recycled gypsum

The main target of the EoW criteria is to ensure that the product is suitable as direct input in production (Villanueva & Eder, 2011).

Existing specifications for recycled gypsum are country-specific and even company-specific quality parameters limit values. In 2012, different quality criteria for recycled gypsum are found in the European context: draft from the German Gypsum Association (BV Gips) in Germany⁵, PAS 109:2008 in the UK (WRAP & BSI, 2008)⁶, as well as other commercial specifications developed by Gypsum recyclers, Plasterboard Manufacturers or Eurogypsum Member Associations. Table 1.2 compiles the values and ranges found for each parameter, based on the analysis of the diverse existing quality criteria.

BV Gips draft-quality criteria presents the most restrictive limit values. This draft is based on previous studies regarding natural and FGD gypsum comparative assessment (Beckert, 1990). On the other hand, PAS 109:2008 also covers open-loop recycling, and some limit values are therefore less restrictive. Italian Gypsum Association and BV Gips set the same toxicological parameters limit values, while the Belgian Gypsum Association and GRI provide no information on this issue. The GtoG project worked to reach harmonized voluntary guidelines to establish quality parameters for the recycled gypsum covering technical and toxicological criteria (see Chapter 4).

⁵ This draft was reviewed in 2013. The last updated can be found in the document: Recycled gypsum initial test for recycling plants, quality management, quality requirements and analysis methods in Germany (Bundesverband der Gipsindustrie e.V., 2013)

⁶ In 2013, PAS 109:2013 superseded PAS 109:2008, which is withdrawn.

Chapter 1

Table 1.2. Recycled gypsum and the diverse quality criteria in 2012

Technical parameters	BV Gips	PAS 109:2008	IT	BE	GRI
Particle size (mm)	≤ 1.00 ^a	≤ 16.00 ^b	≤ 120.00	Custom	≤ 13.00 ^c
Free moisture (% w/w)	≤ 5.00	-	< 5.00	< 10.00	< 10.00
Purity - calcium sulphate dihydrate (% w/w)	> 85.00	> 85.00	> 75.00	> 90.00	^d
Total organic carbon TOC (% w/w)	< 0.50 ^e	< 1.00	< 1.00	< 1.50	< 1.00
Magnesium salts, water soluble, MgO (% w/w)	< 0.02 ^f	< 0.10	< 0.10	< 0.10	< 0.10
Sodium salts, water soluble, Na ₂ O (% w/w)	< 0.02 ^g	< 0.06	< 0.05	< 0.05	< 0.06
Potassium salts, water soluble, K ₂ O (% w/w)	< 0.02	-	< 0.05	< 0.05	-
Soluble Chloride, Cl (% w/w)	< 0.01	< 0.01	< 0.01	< 0.02	< 0.02
Ph	5.0 - 9.0	-	5.0 - 9.0	5.0 - 9.0	7.0 - 9.0
Toxicological parameters					
As (mg/kg)	< 4.00	< 5.23	< 4.00	-	-
Be (mg/kg)	< 0.70	-	< 0.70	-	-
Pb (mg/kg)	< 22.00	< 31.90	< 22.00	-	-
Cd (mg/kg)	< 0.50	< 0.30	< 0.50	-	-
Cr (mg/kg)	< 25.00	< 17.90	< 25.00	-	-
Co (mg/kg)	< 4.00	-	< 4.00	-	-
Cu (mg/kg)	< 14.00	< 32.80	< 14.00	-	-
Mn (mg/kg)	< 200.00	-	< 200.00	-	-
Ni (mg/kg)	< 13.00	< 7.31	< 13.00	-	-
Hg (mg/kg)	< 1.30	< 2.00	< 1.30	-	-
Se (mg/kg)	< 16.00	< 7.37	< 16.00	-	-
Te (mg/kg)	< 0.30	-	< 0.30	-	-
Tl (mg/kg)	< 0.40	-	< 0.40	-	-
V (mg/kg)	< 26.00	-	< 26.00	-	-
Zn (mg/kg)	< 50.00	< 40.30	< 50.00	-	-
Free of asbestos	yes	yes	yes	yes	yes
Radioactivity according to RP 112 (index)	< 0.50	-	< 0.50	< 0.50	-

- No indication from respondents

^a Particle size higher values if agreement

^b Particle size distribution in figure 2.29 of the document

^c Particle size 50% of the particles are bigger than 0.5 mm.

^d Purity: max 5% points (weight) less than what the gypsum plants have supplied to the market during the last 20 years.

^e TOC up to 1% if special agreement

^f MgO up to 0.1% if special agreement

^g Na₂O up to 0.06% if special agreement

1.4. Conclusions

This paper shows findings on gypsum waste management in 10 European countries: Austria, Belgium, Germany, Denmark, France, Italy, the Netherlands, Spain, Poland and the United Kingdom. In addition,

a brief overview of recycled gypsum quality criteria is provided. The main conclusions that can be outlined from this investigation are:

- Most of the recyclable gypsum waste generated and recycled, both in the EU-27 and in each of the countries under study, corresponds to plasterboard waste.
- Pre-consumer gypsum waste is being recycled forming part of the manufacturer's waste avoidance corporate policy. The manufacturer is usually processing its own production waste.
- Post-consumer recycled gypsum is being successfully reincorporated in the plasterboard manufacturing process in France, Belgium, Denmark, the Netherlands and the UK.
- Most of the manufacturers that are currently reincorporating post-consumer recycled gypsum in their process are working with external recyclers apart from their own internal recycling plants.
- The correct implementation of Council Decision 2003/33/EC impacts gypsum waste landfilling and may increase the charges for disposing gypsum waste, which could enhance the competitiveness of the recycling solution compared to local landfills. However, evidence of monocell landfills operation is only found in Belgium, France and the UK.
- In 2012, different quality criteria for recycled gypsum are found in the European context: draft from the German Gypsum Association (BV Gips) in Germany, PAS 109:2008 in the UK (WRAP & BSI, 2008), as well as other commercial specifications developed by Gypsum recyclers, Plasterboard Manufacturers or Eurogypsum Member Associations. The GtoG project is now working to reach harmonized voluntary guidelines to establish quality parameters for the recycled gypsum covering technical and toxicological criteria.

References

- Barbudo, A., Galvín, A. P., Agrela, F., Ayuso, J., & Jiménez, J. R. (2012). Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes. *Waste Management*, 32(6), 1229–35.
<http://doi.org/10.1016/j.wasman.2012.02.005>
- Beckert, J. (1990). Comparison of natural gypsum and FGD gypsum: studies for a comparative assessment of the health impact of natural gypsum and FGD gypsum from coal-fired power plants with a view to their use in the manufacture of building materials. (V. T.-W. S. Essen VGB-Kraftwerkstechnik GmbH, Ed.).
- Bundesverband der Gipsindustrie e.V. (2013). Recycled gypsum (RC-gypsum). Initial test for recycling plants, quality management, quality requirements and analysis methods. Retrieved 4 May 2016, from http://www.gips.de/wp-content/uploads/downloads/2014/03/Anlage-1a_Gipsrecycling_engl.pdf
- Delgado, L., Sofia-Catarino, A., Eder, P., Litten, D., Luo, Z., & Villanueva, A. (2009). End of waste criteria. Final Report.
- European Commission. Proposal for a Directive of the European Parliament and the Council (2014).
- European Commission (DG ENV). (2011). Service Contract on Management of Construction and Demolition Waste - SR1. Final Report Task 2. A project under the Framework contract ENV.G.4/FRA/2008/0112. Retrieved 17 January 2016, from http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf
- European Parliament and the Council of the European Union. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain

- Directives. Retrieved 12 April 2015, from <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:en:PDF>
- European Topic Centre on Sustainable Consumption and Production - EOINET. (2009). Country factsheet - Belgium. Retrieved 21 December 2014, from http://scp.eionet.europa.eu/facts/factsheets_waste/2011_edition/factsheet?country=BE
- European Topic Centre on Sustainable Consumption and Production - EOINET. (2012). Country factsheet - The Netherlands. Retrieved from http://scp.eionet.europa.eu/facts/factsheets_waste/2009_edition/factsheet?country=NL
- Eurostat. (2013). PRODCOM ANNUAL SOLD (NACE Rev.2.) Eurostat PRCCODE: 23522000, 23621050 and 23621090. Retrieved from <http://epp.eurostat.ec.europa.eu/portal/page/portal/prodcom/data/database>
- Fischer, C., Lehner, M., & McKinnon, D. L. (2012). Overview of the use of landfill taxes in Europe.
- GtoG project. (2013). Life+ Gypsum to Gypsum (GtoG) project 'From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry' LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4191
- Jang, Y.-C., & Townsend, T. (2001). Sulfate leaching from recovered construction and demolition debris fines. *Advances in Environmental Research*, 5(3), 203–217. [http://doi.org/10.1016/S1093-0191\(00\)00056-3](http://doi.org/10.1016/S1093-0191(00)00056-3)
- Lee, S., Xu, Q., Booth, M., Townsend, T. G., Chadik, P., & Bitton, G. (2006). Reduced sulfur compounds in gas from construction and demolition debris landfills. *Waste Management*, 26(5), 526–533. <http://doi.org/10.1016/j.wasman.2005.10.010>
- OVAM. Milieuverantwoord Materiaalgebruik en Afvalbeheer in de Bouw. Sectoraal Uitvoeringsplan (2007). Belgium (Flanders region).
- Silva, R. V., de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, 65, 201–217. <http://doi.org/10.1016/j.conbuildmat.2014.04.117>
- Sun, W., & Barlaz, M. a. (2015). Measurement of chemical leaching potential of sulfate from landfill disposed sulfate containing wastes. *Waste Management*, 36, 191–196. <http://doi.org/10.1016/j.wasman.2014.11.014>
- The Commission of the European Communities. Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 74/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of C (2000). European union: Official Journal of the European union. Retrieved from <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32000D0532&from=EN>
- The Council of the European Union. (2003). Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex to Directive 1999/31/EC (2003/33/EC). Official Journal of the European Communities, L 11/27-11/49.
- Tovar-Rodríguez, G., Barra, M., Pialarissi, S., Aponte, D., & Vázquez, E. (2013). Expansion of mortars with gypsum contaminated fine recycled aggregates. *Construction and Building Materials*, 38, 1211–1220. <http://doi.org/10.1016/j.conbuildmat.2012.09.059>
- Villanueva, A., & Eder, P. (2011). End-of-waste criteria for waste paper: Technical proposals. <http://doi.org/10.2791/57814>
- Williams, B. (2008). *Europroms PRODCOM Data, User Guide*, 1–18.
- WRAP and Environmental Resources Management Ltd (ERM). (2008). *Technical Report: Life Cycle Assessment of Plasterboard*.
- WRAP, & BSI. (2008). PAS 109:2008. Specification for the production of recycled gypsum from waste plasterboard.

- WRAP, & BSI. (2013). PAS 109:2013. Specification for the production of reprocessed gypsum from waste plasterboard. Retrieved 4 May 2016, from [http://www.wrap.org.uk/sites/files/wrap/PAS109 \(2013\).pdf](http://www.wrap.org.uk/sites/files/wrap/PAS109%20(2013).pdf)
- WRAP, & Environment Agency. (2013). Quality Protocol. Gypsum. End of waste criteria for the production and use of recycled gypsum from waste plasterboard.
- Xu, Q., & Townsend, T. (2014). Factors affecting temporal H₂S emission at construction and demolition (C&D) debris landfills. *Chemosphere*, 96, 105–11. <http://doi.org/10.1016/j.chemosphere.2013.07.052>

2 LIFE CYCLE ENERGY AND MATERIAL FLOWS

CHAPTER OVERVIEW

This chapter evaluates the impacts, in terms of primary energy use and greenhouse gas (GHG) emissions, of different levels of plasterboard recycling. To this end, a life cycle model of gypsum mass flows in the EU is formulated, in the reference year 2013. This model constitutes the basis of the quantitative scenario analysis. The current situation (“2013 base case”) is compared with two scenarios: a worst case scenario (“Zero recycling case”), and a best case scenario of zero gypsum waste (GW) sent to landfill, corresponding to 18.7% recycled gypsum (RG) in new plasterboard (“High recycling case”).

Published as

Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources, Conservation and Recycling*, 108, 171–181. DOI: <http://dx.doi.org/10.1016/j.resconrec.2016.01.014>

Main research questions addressed and relation to other chapters

	Research question (and related specific objective in parentheses)	Brief answer and → Relation with other chapters
<div> <div>Chapter 1. Gypsum waste generation and management</div> <div>Chapter 2. Life cycle energy and material flows</div> <div>Chapter 3. Factors influencing post-consumer gypsum recycling</div> <div>PART II: MACRO-LEVEL</div> </div>	How do different levels of gypsum recycling correlate with the primary energy use and the GHG emissions of the plasterboard life cycle in the EU? (O2)	<p>The total GHG emission is 9% smaller in the high recycling case, mainly due to landfill emissions (H₂S and CH₄) when plasterboard is deposited in mixed waste landfills.</p> <p>→ This chapter focuses on gypsum plasterboard because of two main reasons. First, plasterboard makes up more than 4/5 of the gypsum products consumed in the EU, as assessed in Chapter 1. Second, the required background data from the existing literature mainly refers to plasterboard (e.g. Life Cycle Inventory references).</p> <p>→ Results from the present chapter impacts the formulation of monitoring indicators on environmental aspects in Chapter 5 (i.e. DE2 and RE1). In addition, conclusions from this chapter influence the selection of best practices affecting GHG emissions (e.g. RE1) in Chapter 6.</p>
<div> <div>Chapter 4. Physical and mechanical characterization</div> <div>Chapter 5. End-of-life case studies analysis</div> <div>Chapter 6. Best practices in the end-of-life stage</div> <div>PART III. MICRO-LEVEL</div> </div>		

2.1. Introduction

Working towards greater resource efficiency in the construction sector is essential for addressing global issues such as mitigating climate change and moving to a more circular economy. Moreover, the circular economy principles enables the sector to fulfil the resource efficiency agenda established under the Europe 2020 Strategy for smart, sustainable and inclusive growth (Antink et al, 2014; European Commission, 2014a). A circular economy system keeps the added value in products for as long as possible and reduces waste. This strategy of turning waste into a resource is an essential part of increasing resource efficiency and “closing the loop” in a circular economy (European Commission, 2014c). Closed-loop supply chain management entails the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time (Govindan et al., 2014). It implies forward and reverse supply chains operating simultaneously, and closed-loop recycling as a necessary link for its success.

Gypsum is a versatile construction material that can effectively close the material loop, being fully and eternally recyclable. Unfortunately, a large proportion of gypsum waste is currently being landfilled worldwide, including building plaster, gypsum blocks and plasterboard waste (the latter being the most common recyclable gypsum waste generated in Europe). However, the processing of gypsum waste into high quality recycled gypsum is possible, already occurring in different regions of Belgium, Finland, France, Denmark, Sweden, the Netherlands and the United Kingdom, in which recycling systems are now operating and supplying plasterboard manufacturers. Moreover, all over Europe efforts are being made to increase the recycling rate of this material, boosted by the development of the Life+ GtoG project, which from January 2013 has been working to transform the gypsum waste market, with the aim of achieving higher gypsum recycling rates in Europe (GtoG project, 2013a). This approach contributes to mitigating primary resource depletion, contributing at the same time to minimizing construction and demolition (C&D) waste streams sent to landfills.

Knowledge of the quantities of waste streams generated constitutes an essential step in the development of an appropriate scheme for their management (Kourmpanis et al., 2008). Material flow analysis (MFA) is an analytical approach to quantifying the system-wide flows and stocks of materials associated with a defined product. Life-cycle assessment (LCA) is the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (International Standard, 2006a). Together, these approaches provide the means to evaluate the environmental implications of gypsum plasterboard recycling.

Consequently, the formulation of a life cycle model associated with gypsum plasterboard material flows in the European Union, in the reference year 2013, constitutes the basis of this investigation. It enables establishing the relations between gypsum recycling, energy use and GHG emissions, in a life cycle perspective. Scenario-based modelling has been conducted for this purpose, evaluating the impact of different levels of recycled gypsum reincorporated in the manufacturing process. To our knowledge, this analysis is the first to comprehensively quantify the system-wide life cycle energy and mass flows

associated with gypsum plasterboard in EU-27, and to model their changes under varying levels of plasterboard recycling.

2.1. The life cycle of gypsum plasterboard

The life cycle of gypsum plasterboard typically begins with the extraction and processing of raw materials, continues with the manufacture and use of the plasterboard, and then reaches end-of-life (EoL) that involves either landfilling, recycling or other forms of recovery (Fig. 2.1). These life cycle processes are described in the following sub-sections.

Fig. 2.1. Life cycle system-wide mass flows associated with gypsum plasterboard. The numbers indicate million tonnes of material flows in the EU-27 in the reference year 2013 and is the basis of scenario “2013 base case” described in “Scenario projections of plasterboard recycling” section. 2.3. PB: plasterboard; EoL: End-of-Life. Reverse logistics shown with dashed line

2.1.1. Supply of gypsum and other inputs

Sources of gypsum for plasterboard production include gypsum mining, flue gas desulfurization (FGD) gypsum, and recycled products. Other required plasterboard inputs include paper and additives.

- Natural gypsum

Natural gypsum is a mineral composed of calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Data on gypsum mine production are provided by several different sources (Eurostat, 2013b; Roskill, 2014; USGS, 2013). The authors consider the annual publication Roskill Report (Roskill, 2014) to be the most authoritative estimate, as it is based on data from the other two references (USGS, 2013) as well as company reports and trade press. According to this report, 24.91 million tonnes (Mt) of natural gypsum were mined in the EU-27 in 2013. Globally, 139.38 Mt of gypsum was mined in 2013. In addition to plasterboard production, gypsum is also used in other plaster products, in cement manufacture, and for agricultural applications. Gypsum mining involves drilling and blasting the rock, after which it is loaded onto trucks using front-end loaders and mechanical shovels (Venta, 1997). Gypsum extraction processes typically use diesel fuel and electric power. World resources of natural gypsum are considered to be large, and are expected to be sufficient to meet demand well into the future (Roskill, 2014). Although

there is no global shortage of natural gypsum, mining can cause impacts in terms of land occupation, energy use and potential loss in biodiversity (European Commission, 2010).

- FGD gypsum

The gypsum industry uses synthetic gypsum that is a by-product of industrial processes used to reduce sulphur emissions from coal-fired power plants. Flue-gas desulphurization (FGD) systems consist of wet scrubbers that remove sulphur dioxide (SO₂) through the reaction with an alkaline material such as lime. This process is shown in Eq. (1), where lime slurry (Ca(OH)₂) is used to remove the SO₂ from the flue gas, creating calcium sulphite (CaSO₃) and water.

For this by-product to be used as raw material for plasterboard production, it must be further oxidized (Eq. (2)). Additional energy is required for this forced oxidation to produce calcium sulphate dihydrate (CaSO₄ · 2H₂O), a saleable gypsum product sourced by the plasterboard industry. This oxidation energy is estimated by (WRAP, 2008) at 1.4 MJ of coal combustion per kg of FGD gypsum produced.

FGD gypsum is produced in several EU countries, but is concentrated in Germany where 6 Mt of the estimated total EU production of 8 Mt was produced in 2013 (Roskill, 2014). Of this total production, and based on the latest published ECOBA statistics (ECOBA, 2010), 50.6% was used for plasterboard manufacturing in the EU-15 in 2010. This is an average figure; in some EU countries such as France, Spain and Italy, the use of FGD gypsum is limited or non-existent, while the use is higher in others such as Belgium, Germany and Scandinavian countries. There are currently EU and national political debates about sustainable energy, the EU commitment to reduce CO₂ emissions, secure energy supply including the need to balance the energy mix, the growing need to use renewable energy sources and the development of new efficient technologies for power generation. Together, these factors are expected to reduce coal use and thus the production of FGD gypsum within the coming decades, particularly in Germany and other western EU member states.

Other sources of synthetic gypsum, such as phosphogypsum, fluorogypsum and titanogypsum, have not been considered here as they are usually consumed by other markets (such as cement manufacture) and not used in significant amounts in plasterboard manufacturing in the EU-27 (Roskill, 2014).

- Recycled gypsum

Recycled gypsum is the result of controlled processing of waste plasterboard to separate the gypsum, paper lining, and any impurities, such that it can be used in lieu of natural or synthetic gypsum. The recycled gypsum can be either pre-consumer or post-consumer. As a general rule, pre-consumer gypsum waste is cleaner than post-consumer gypsum waste. Pre-consumer recycled gypsum is material diverted

from the waste stream during a manufacturing process (International Standard, 1999). Post-consumer recycled gypsum usually comes from recyclers (CRI, 2010), mainly from C&D gypsum waste. Recycled gypsum is usually in the form of a fine or sandy powder, or a small-aggregate type material (WRAP, 2008).

Plasterboard has been identified as one of the major components contributing to the total potential recycled content of a construction project, in terms of recycled value (Emery et al., 2007). Following the need to reduce the volume of C&D waste sent to landfill and to increase the efficiency of using resources, the use of recycled gypsum is expected to grow in the coming years.

- Paper and additives

Two other inputs to plasterboard production are required. Facing paper is applied to both sides of the gypsum plaster core, providing most of the tensile strength to the plasterboard. Recycled paper is typically used as plasterboard lining in the EU-27, according to ELCD process data (EC JRC, 2007). Furthermore, small amounts of additives such as starch, lignin, perlite, vermiculite, soap foam, retarders, shredded paper, and accelerators are also used.

2.1.2. Plasterboard manufacturing

During plasterboard manufacturing, the process inputs including natural, FGD and recycled gypsum, paper and additives are combined to form the gypsum plasterboard product. Regardless of the source of the gypsum raw material, the calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is first heated (calcined) and partially dehydrated to form calcium sulphate hemihydrate ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$), called stucco in the industry and also popularly known as “Plaster of Paris” (Eq. (3)).

The process of calcining (also known as calcination) is commonly associated with the heat-driven removal of CO_2 from limestone to produce lime, but more generally refers to the thermal treatment of solid materials and need not involve reaction emissions of CO_2 . Calcination of gypsum raw material results in partial dehydration of the mineral, with the only reaction emission being water vapour.

Next, measured quantities of calcium sulphate hemihydrate, additives and water are mixed, creating a gypsum slurry. This slurry is spread in a uniform thickness onto a layer of facing paper, and then covered by another layer of facing paper. The gypsum then re-hydrates to form hard calcium sulphate dihydrate (Eq. (4)).

The gypsum core of the manufactured plasterboard takes around four to five minutes to harden (Roskill, 2014). When the hydration is completed, the gypsum has been chemically restored to its rock-like state as found in nature (dihydrate), forming the gypsum core of the plasterboard, encased in paper. The resulting boards are then cut to the desired length and sent to a drying kiln. Excess water is driven off in

drying kiln (WARM, 2014; Roskill, 2014; Venta, 1997). The finished sheets are then prepared for shipment.

GHG emissions and energy consumption in plasterboard manufacturing mainly come from:

- Manufacturing of paper (paper making process) and additives.
- Pre-processing including size reduction (crushing and grinding) and pre-drying operations of gypsum raw material before calcination.
- Gypsum calcination (calcium sulphate dihydrate to stucco), also known as stucco production (WRAP, 2008), which is a reversible process, making gypsum an indefinitely recyclable material.
- Plasterboard production, which involves the mixing of the stucco slurry, paper feeding, setting, cutting and drying of plasterboard in drying kilns.

Previous studies in the US (WARM, 2014) estimate the following energy use breakdown within the plasterboard production stages: 13% for raw material obtention, 3% for raw material transportation, and 85% for plasterboard manufacturing. Due to the nature of the chemical process and materials used, there are no non-energy process emissions of GHGs from plasterboard manufacturing (WARM, 2014)

2.1.3. Plasterboard use in buildings: construction, use and end-of-life (EoL)

Gypsum plasterboard as a material provides good levels of acoustic and thermal insulation, and as a system, the cavities behind the main face can accommodate further insulation. This product also offers a high level of fire protection, due to gypsum's water content and non-combustible nature (European Commission, 2010). It is used for partitions, ceilings and lining of walls. Apart from its use in new construction works, it is extended in refurbishment solutions for thermally insulating existing buildings, being part of improved wall insulation solutions (Dodoo, Gustavsson, & Sathre, 2010), lowered ceilings, creating air voids below old ceilings or supporting thermal insulation (Bojić et al., 2012).

By using plasterboard walls, C&D waste generation per square meter of build surface can be reduced 16% by weight and 3% by volume, compared to using traditional brick partitions (Villoria Sáez et al., 2014). Plasterboard use involves less involvement of labour, short installation time and smooth wall surface quality (Tam et al., 2014). A progressive change in building procedures, substituting internal brick walls with plasterboard products, has being reported even in countries where brick walls have been traditionally used (Herrero et al., 2013).

Plasterboard is widely used in most of the European countries, and those with the strongest plasterboard use are usually the lowest consumers of other plaster products (mainly used in traditional masonry construction). A well-established plasterboard market currently exists in Germany, France and the United Kingdom, covering more than 53% of the European market volume (EC JRC, 2007). The highest consumption of plasterboard (in m² per capita) is found in Denmark, France, Ireland, Austria, Finland, Sweden and the United Kingdom (GtoG project, 2013b).

2.1.4. *End-of-life options for gypsum plasterboard*

Pre-consumer gypsum waste generated during the manufacturing process is usually known as production waste, and includes out-of-specification boards and boards damaged during packaging. The recycling of this production waste is commonly done as part of corporate waste avoidance policy.

Once the material leaves the manufacturing facility, damaged or unused plasterboard from distributors and retailers and fit-out waste from installation (offcuts, damaged or unused on site) becomes construction waste. Recyclable demolition plasterboard waste is usually strip-out waste resulting from deconstruction or selective demolition works, which involves dismantling, segregation and storage of gypsum waste. Effective deconstruction operations are crucial to maximizing the recyclable gypsum waste stream. Manual dismantling and segregation operations of plasterboard waste are assumed to be the common practice during deconstruction in our scenarios. The use of mechanical equipment (e.g. sorting grabs) are only observed on a case-by-case basis, particularly when a high amount of gypsum waste generation is foreseen (GtoG project, 2015).

Detailed gypsum waste generation and disposal statistics are unavailable at the European or national levels. The authors have found only one estimate, that about 4 Mt of gypsum waste are generated in Europe annually (only considering construction waste), of which between 25% and 30% comes from plasterboard (European Commission, 2011). Buildings currently being deconstructed in Europe contain other plaster products but relatively little plasterboard, as plasterboard was not commonly used when these buildings were constructed, e.g. 50-60 years ago. Plasterboard content in C&D waste is expected to increase in the future, as buildings constructed more recently reach the end of their service lives and are deconstructed.

The level of landfilling of C&D waste varies greatly across the EU, from 10% to 90% (European Commission, 2011). Countries such as Cyprus, Czech Republic, Greece, Hungary, Poland, Portugal and Spain currently experience high landfilling rates. However, estimates are not available for all EU countries, and high variability is observed between different data sources, likely due to the lack of standardized control and reporting mechanisms.

High concentrations of hydrogen sulphide (H_2S) at C&D debris landfills are attributed to H_2S generation from the disposal of gypsum plasterboard. Council Decision 2003/33/EC established that “Non-hazardous gypsum-based material should be disposed of only in landfills for non-hazardous waste in cells where no biodegradable waste is accepted” (The Council of the European Union, 2003). This is because gypsum waste is a high-sulphate waste, and if it is deposited in normal cells in non-hazardous landfills, its sulphate can break down into, amongst other substances, hydrogen sulphide (H_2S). This is a colourless, flammable, extremely hazardous gas associated with environmental and health effects, that even in low concentrations creates odour problems (OSHA and US, 2005). The emission rate of H_2S is variable and depends on different factors such as soil moisture, H_2S concentration and temperature (Xu and Townsend, 2014). In order to comply with this Council Decision, plasterboard or other gypsum waste should be disposed of in monocell landfills, meaning the disposal of plasterboard in separate

landfill cells for high sulphate materials. However, its implementation is not always upheld, and thus gypsum waste is, in many cases, landfilled under improper conditions (European Commission (DG ENV), 2011).

Methane (CH_4) and carbon dioxide (CO_2) emissions are also generated when plasterboard is landfilled, formed during the degradation of the paper content. Methane produced in monocell landfills is released at a low rate, and is likely to undergo oxidation to CO_2 in the surface layers of the site before being released to the atmosphere. In mixed waste landfills, however, methane from the degradation of plasterboard facing paper is likely to be released along with other landfill gases (WRAP, 2008). Some of this gas may be collected and either flared or used for energy, whereas the remainder will escape to the atmosphere as fugitive methane emissions.

Plasterboard waste is currently processed by dedicated gypsum recyclers, which usually receive gypsum waste from transfer stations, waste management companies, waste sorting facilities, or directly from jobsites, in conformance with relevant acceptance criteria. Several mechanical steps, such as grinding and sieving, take place for processing the gypsum waste into recycled gypsum. Plasterboard waste may also be used for other applications. For example, the agricultural use of gypsum as soil treatment is widespread in countries such as the UK. Cement production, manufacture of other construction products, soil stabilization and binding are some of the documented open-loop recycling practices (WRAP and BSI, 2013). In Europe, gypsum recyclers operate in France, Belgium, the Netherlands, Luxembourg, Finland, the UK, Denmark, and Sweden. The amount processed is considered confidential and thus not reported by the gypsum recyclers.

Most of the EU countries are currently facing challenges in the management of gypsum waste, which is variable depending on each national context. For example, the emergence of gypsum recycling facilities is only expected to occur under certain conditions related to policy effectiveness and control. An important factor is the competitiveness of the recycling route, mainly determined by the cost of landfill disposal or a landfill ban. On the other hand, even when a market for recycled gypsum exists in a region, non-recyclable gypsum waste can be generated when demolition rather than deconstruction processes are used, which rely on different parameters such as manpower, cost, space and environmental focus of the waste owner. Non-recyclable gypsum waste does not comply with gypsum recyclers' acceptance criteria that usually limit impurities $\leq 2\%$ and wet gypsum $\leq 10\%$ (GtoG project, 2015). Moreover, the difficulty of separating gypsum waste from a mixed waste stream (e.g. when the gypsum waste is not source segregated) increases the rate of landfilling. Furthermore, while alternative destinations that are lower in the waste hierarchy (e.g. backfilling) can limit or even disable closed-loop gypsum recycling, a reduced availability of natural and/or FGD gypsum might encourage the recycling of gypsum.

2.2. Scenario projections of plasterboard recycling

A life cycle model of gypsum plasterboard mass flows is first developed (Fig. 2.1), which describes all significant material streams associated with the life cycle of gypsum plasterboard consumed in the EU-27 in the reference year 2013. System boundaries include the material supply, manufacturing, installation and EoL stages. These processes are detailed in Table 2.1. Based on this model, the known flows of selected materials are quantified: natural gypsum and new plasterboard. Principles of mass balance are then applied to determine flows of other materials, e.g. FGD gypsum, facing paper, waste plasterboard, and recycled gypsum.

Table 2.1. Life cycle stages of gypsum plasterboard, and processes within each stage

Stage	Process
Raw material supply, including processing of secondary material input	Gypsum mining
	FGD gypsum
	Paper
	Additives
	Waste processing (Production waste)
	Total raw material supply
Transport of raw material and secondary material to the manufacturer	Transport natural gypsum
	Transport FGD
	Transport recycled gypsum
	Transport paper
	Transport additives
	Total transport of raw and secondary materials
Manufacture of plasterboard and all upstream processes	Plasterboard manufacturing (Pre-processing)
	Plasterboard manufacturing (Calcination, production)
	Total plasterboard manufacturing
Transport of plasterboard to the building site	Transport of plasterboard to the jobsite
Plasterboard installation and/or deconstruction	Building Construction, Use and EoL
Transport of the post-consumer plasterboard waste to waste processing	Transport of post-consumer PB waste to waste processing
Waste processing of post-consumer plasterboard waste	Waste processing
Final disposal of plasterboard	Transport of post-consumer PB waste to landfill
	Operation of landfill site
	Biogenic emissions from landfill
	Total final disposal

Scenario-based modelling is conducted to evaluate the GHG emissions and primary energy implications of different levels of plasterboard recycling in EU-27. Our analysis is based on the mass flows associated with plasterboard installed in the reference year 2013. Quantitative scenario analysis is then conducted to determine how system-wide material flows, energy use and GHG emissions would be affected by increased or decreased levels of recycled gypsum content in new plasterboard production. The actual situation in 2013 that we term “2013 base case” (5% recycled gypsum content of new plasterboard) is

compared with two alternative scenarios: “Zero recycling case” (0% recycled gypsum) and “High recycling case” (18.7% recycled gypsum reincorporated, corresponding to zero post-consumer plasterboard waste sent to landfill). We study how variations of selected parameters would affect the environmental impacts associated with gypsum plasterboard over its life cycle. Both the 2013 base case and high recycling case consider an input of 4% of pre-consumer recycled gypsum, as sources estimate that 35% of production is lost as waste (Roskill, 2014). It should be noted that alternative scenarios are devised in order to enable comparative assessment of the 2013 base case against two extreme recycling rates: 0% and 18.7%. The zero recycling case would be achievable under the worst of circumstances, although pre-consumer gypsum waste is commonly recycled. In contrast, the high recycling case would require 100% material recovery which is quite optimistic, thus represents an asymptote to be targeted. Although highly effective deconstruction techniques exist, they currently do not result in total gypsum waste segregation.

Life cycle inventory (LCI) data for the analysis is taken from published literature and LCI databases. Data was selected from a variety of sources in order to meet ISO data quality requirements (International Standard, 2006b).

2.2.1. *Material flows*

Based on 5 European references of normal/standard plasterboard (Table 2.2), the statistical average of paper and additives contained in the plasterboard produced in the EU-27 is formulated (Table 2.3). For the case of Environmental Product Declarations (EPDs), only those available, reporting complete data for standard plasterboard and verified by an independent third party have been taken into account. The FGD gypsum reference proportion (26.9%) in plasterboard are estimated by assuming 35.9% of recovered content in plasterboard (EU JRC, 2007), which includes recovered paper (4.0%), recycled (5.0%) and FGD gypsum. This is termed the “Reference plasterboard”. It is important to note that the proportion of each type of gypsum, paper and additives may vary by country and/or by manufacturer. The Technical Report of Life Cycle Assessment of Plasterboard (WRAP and ERM, 2008) is the only available European reference currently providing detailed data of the EoL stage (modules C1 - C4 according to EN 15804). Natural, FGD and recycled gypsum have been considered the main feedstock material of the Reference plasterboard.

The amount of plasterboard consumed in the EU-27 in 2013 is estimated by analysing statistics on the production of manufactured goods. Figures in the database are provided in square metres (Eurostat, 2013a). The four digits 2362 identify the plasterboard industry, according to the classification of the producing enterprise given by the Statistical Classification of Economic Activities in the European Community (NACE). The code 23621050 refers to boards, sheets, panels, tiles and similar articles of plaster or of compositions based on plaster, faced or reinforced with paper or paperboard only (excluding articles agglomerated with plaster, ornamented). The “Apparent consumption” has been taken as the indicator that reflects the proportion of installed plasterboard, by adding the imports quantity to the production quantity, and subtracting exports (Williams, 2008), based on data in the Prodcom list (NACE Rev.2), Sold production, exports and imports. It is therefore estimated that 1,073,464,249 m² of

plasterboard were consumed in the EU-27 in 2013. This equals 10.73 Mt of weight material, by assuming 10 kg/m² as the standard plasterboard density, as considered in the EU process data set, available in the EU ELCD database and representative of the EU-27 region for the period 2007-2014.

Table 2.2. Formulation of reference standard plasterboard, based on several European LCI references. ^aCalculation from baseline scenario mass flows

Reference	Region	Thickness (mm)	Density (kg/m ²)	Contents in final product (% by weight)				
				Natural gypsum	Synthetic gypsum	Recycled (pre+post-consumer)	Paper liner	Additives
Bjorklund and Tillman, 1997	SE	13.0	9.0	47.3	47.3	-	4.9	0.5
WRAP, 2008 ^a	GB	12.5	-	33.6	50.8	9.9	4.2	1.5
ELCD database 2.0, 2007	EU-27	12.5	10.0	-	35.9			-
EPD System, 2013	GB	12.5	8.4	0.0	94.5		3.0	2.5
EPD System, 2013	SE	12.5	9.0	45.8	49.7		3.8	0.7

Table 2.3. Composition, by weight percentage, of the considered Reference plasterboard, based on the statistical average of total gypsum, paper and additives in plasterboard produced in the EU-27. Recovered content includes FGD gypsum, recycled gypsum and recycled paper.

Raw materials in Plasterboard	Reference PB (%)
Total gypsum	94.7
Natural gypsum	62.8
FGD gypsum	26.9
Recycled gypsum	5.0
Pre-consumer	4.0
Post-consumer	1.0
Facing paper	4.0
Additives	1.3
Total recovered content	35.9

Plasterboard installation, dismantling or demolition generates post-consumer plasterboard waste. The paucity of reliable references studying its generation in Europe is a major challenge we faced in modelling the EoL mass balances. Our estimates are based on the amount of plasterboard waste generated in 8 European member states (Belgium, Denmark, Greece, Spain, France, the Netherlands, Poland and the United Kingdom) assessed in the framework of the GtoG project, equalling 1.15 Mt (GtoG project, 2013b). In these 8 countries, the total C&D waste generated amounted to around 499 Mt in 2012, the latest update of the Eurostat database (Eurostat, 2012b). This means an estimated rate of post-consumer plasterboard waste of 0.23% of the total C&D waste in the EU-27, equivalent to 1.9 Mt, whose final route is either recycling, landfill disposal or other uses including re-use, recovery and open loop recycling. In all scenarios, it is assumed that the same amount following the recycling route in the 2013 base case is sent to other uses. The remaining waste is considered to be deposited in landfill.

On this basis, it is determined the amount of post-consumer plasterboard waste following the recycling route, as the post-consumer recycled gypsum reincorporation rate into the manufacturing process is a known value in our model (i.e. 1% by weight of new plasterboard in the 2013 base case). It is assumed that, after processing the plasterboard waste, 7.5% by weight will result in waste paper (a mix of lining paper with gypsum residues), which is sent to the paper industry for recycling, and therefore considered outside the boundaries of this investigation. The resulting amount of post and pre-consumer recycled gypsum forms part of the total amount of recycled gypsum reincorporated into the process (e.g. 5% by weight of new plasterboard in the 2013 base case).

2.2.2. *Primary energy and GHG emissions*

Based on these system-wide material flows, energy and GHG intensity factors are applied to each process to estimate overall energy use and GHG emissions. Primary energy and GHG emission intensity factors for gypsum mining, paper and additives manufacture are based on Ecoinvent (2012). For the case of plasterboard waste processing, gypsum pre-processing, demolition or deconstruction works and final disposal, data from Doka (2003); Plimmer et al (2007) and WRAP (2008) have been used, as detailed in Table A1.2 in the Appendix 1. Energy and emission intensity factors for deconstruction and waste segregation are used for recycled plasterboard, whereas factors for demolition are used for landfilled plasterboard. The ELCD process data set, together with an Explanatory note (Eurogypsum, 2010), are the main references for obtaining the energy and GHG emissions of the plasterboard manufacturing process. It is assumed that gypsum calcining and plasterboard production processes do not change with increased proportion of recycled gypsum, and only the pre-processing stage, which refers to the size reduction (crushing and grinding) and drying of the gypsum feedstock before calcination, varies in the different scenarios (WRAP, 2008).

Energy and emissions intensity factors for train, truck and ship transport are based on data published by the International Energy Agency for the year 2005 and the European Environment Agency for the year 2011, which are the most recent data found (European Environment Agency, 2011; International Energy Agency, 2008). EU-27 average electricity emissions factor, published by the European Environment Agency, has been utilized in this investigation (EEA, 2008). GHG emissions are quantified as CO₂ equivalents, using global warming potential (GWP) characterization factors over a 100-year time horizon (IPCC, 2013).

For estimating the distances travelled by raw materials, plasterboard, gypsum waste and recycled gypsum, the assumptions detailed in Table 2.4 are made, based on related European LCI references. For the case of natural and FGD gypsum, two transport alternatives are considered, using weighting factors to reflect their potential occurrence. For this purpose, Germany, France and the UK are considered as representative of the EU-27 (EU JRC, 2007). In Case A, most common situation in Europe, natural gypsum is locally sourced (87%) and FGD gypsum is transported from a nearby coal power station (89%). In all other instances, case B applies, which involves raw materials being imported (i.e. natural gypsum transportation is assessed by assuming 87% case A and 13% case B).

For the final disposal stage, our accounting considers the transport and operational burdens associated with the disposal of plasterboard in landfills, as well as emissions from landfills. When paper is deposited in mixed-waste landfills, it can be degraded by anaerobic bacteria, producing CH₄ and CO₂. Landfill emissions are modelled based on data from Plimmer et al. (2007), who used the GasSim2 tool developed for the UK Environmental Agency. In our life cycle model, the direct CO₂ emission from lining paper degradation are disregarded, as it is part of the natural carbon cycle of growth and decomposition (United States Environmental Protection Agency EPA, 2015). It is assumed that 75% percent of the CH₄ produced from the decomposition of lining paper is recovered and flared to CO₂. For simplicity, the energy of the recovered gas and its potential conversion and use is not part of the model. The remaining 25% of produced CH₄ is assumed to escape to the atmosphere (Plimmer et al. 2007). This CH₄ emissions are converted to equivalent CO₂ emission using a global warming potential (GWP) of 34, and include these emissions in our accounting. In a sensitivity analysis two alternatives are also considered: landfilling in a monocell landfill with zero CH₄ emissions, and landfilling in a mixed-waste landfill with only 50% recovery of CH₄.

Table 2.4. Transport details

Materials, products and waste	From	To	Mode	Source	Distance (km)	Baseline	
						Mt/year	Mtkm
Natural gypsum - Case A	Mine or quarry	Manufacturing plant	Road	EPD System, 2013	2.00	7.04	14.09
Natural gypsum - Case B	Mine or quarry (imp)	Manufacturing plant	Road	WRAP, 2008	16.00	7.04	112.72
	Mine or quarry (imp)	Manufacturing plant	Ship	WRAP, 2008	2,730.00	7.04	19,232.60
FGD gypsum - Case A	Coal power station	Manufacturing plant	Road	WRAP, 2008	54.00	3.02	163.13
	Coal power station	Manufacturing plant	Rail	WRAP, 2008	54.00	3.02	163.13
FGD gypsum - Case B	Coal power station (imp)	Manufacturing plant	Road	WRAP, 2008	2.00	3.02	6.04
	Coal power station (imp)	Manufacturing plant	Ship	WRAP, 2008	1,083.00	3.02	3,271.66
Facing paper	Paper production	Manufacturing plant	Road	Average from WRAP, 2008	200.00	0.45	89.01
Additives	Additives production	Manufacturing plant	Road	Considered by authors	200.00	0.15	29.19
Plasterboard	Manufacturing plant	Building site	Road	Average LCI references	189.64	10.73	2,035.72
C&D PB waste	Building site	Waste processing	Road	Average DA1 Report, GtoG	150.00	0.12	18.09
RG (post-consumer)	Waste processing (ext)	Manufacturing plant	Road	Average DA1 Report, GtoG	12.50	0.11	1.40
RG (pre-consumer)	Waste processing (int)	Manufacturing plant	Road	DA1 Report, GtoG	0.00	0.45	0.00
Plasterboard waste	Jobsite or Manuf. plant	Landfill	Road	WRAP, 2008	40.00	1.66	66.45

RG: recycled gypsum

2.3. Results and discussion: Implications of gypsum plasterboard recycling in the EU-27

This section presents the mass flow, primary energy use and GHG emissions implications of the different recycling scenarios.

2.3.1. Mass flow implications

Fig. 2.2 shows the composition by weight percentage of the resulting three plasterboards in the considered scenarios: zero recycling case, 2013 base case and high recycling case. In our model, the natural gypsum used depends on the recycled gypsum content, whereas the FGD gypsum, paper and additives remain fixed in the 3 scenarios. In all cases, natural gypsum dominates the material mass, followed by the FGD gypsum. Recycled gypsum comprises 0.0% of the zero recycling case, 5% of the 2013 base case and 18.7% of the high recycling case plasterboard.

Fig. 2.2. Composition, by weight percentage, of the two plasterboard compositions derived from the alternative scenarios (left and right) and the Reference plasterboard (2013 base case)

The system-wide mass flows in the different scenarios allow us to determine the fate of post-consumer plasterboard waste. In the zero recycling case, 93.6% is landfilled and 6.4% is used for other uses. In the 2013 base case, 87.2% is landfilled, 6.4% is used for other uses, and 6.4% is recycled into plasterboard (closed-loop recycling). This corresponds to 5.0% recycled gypsum content in new plasterboard production. In the high recycling case, 0.0% is landfilled, 6.4% is used for other uses, and 93.6% is recycled into plasterboard (closed-loop recycling), corresponding to a 18.7% recycled content in new plasterboard.

The plasterboard raw gypsum source and post-consumer plasterboard waste fate in the 3 different scenarios is shown in Fig. 2.3. It should be noted that, based on the mass balance equations, the amount of FGD gypsum incorporated equals 3.02 Mt/year, which is less than the 5.17 Mt in 2010 (ECOBA, 2010). It is assumed that this difference may be due to the manufacturing of other non-faced plaster products, outside the scope of this analysis.

Fig. 2.3. Raw material and waste in the 3 different scenarios, in million tonnes per year (Mt/year). PB=plasterboard

In the high recycling case, 1.65 Mt/year of plasterboard waste landfilling is avoided, compared to the 2013 base case. This significant reduction in plasterboard landfilling would contribute to mitigating primary resource depletion and preventing H_2S and CH_4 emissions from landfills.

2.3.2. Primary energy implications

Fig. 2.4 and Fig. 2.5. show the impact, in terms of primary energy use, of increased gypsum recycling in new plasterboard production in the three scenarios. The functional unit (FU) is one square meter of plasterboard consumed.

The highest primary energy use results from reincorporating 18.7% of recycled gypsum (high recycling case), although the energy difference between this value and the other two scenarios is very small: 43.09 MJ/m² in the zero recycling case and 2013 base case and 43.62 MJ/m² in the high recycling case. Increased recycling leads to decreased energy use in gypsum mining, transport of natural gypsum to the manufacturing plant and transport of plasterboard waste to landfill. However, it increases the transport of plasterboard waste to the recycling facility, the energy use for waste processing, the transport of the recycled gypsum to the manufacturing plant and the energy use for gypsum pre-processing.

The plasterboard manufacturing process constitutes around 46% of the plasterboard life cycle's primary energy use (19.75 MJ/m² in the 2013 base case). Variations with increased recycled content are very low: 1% increased energy use with a shift from the 2013 base to the high recycling case, mainly explained by the higher pre-processing energy demand.

Transport of raw materials is responsible for a substantial portion of total energy use. The impacts of transporting natural gypsum in the zero recycling case are reduced by 38% in the high recycling case. The transport of post-consumer plasterboard waste to processing varies from 0.05 MJ/m² in 2013 base

case to 0.68 MJ/m^2 in the high recycling case. However, it is largely offset by primary energy decrease for post-consumer plasterboard waste transported to landfill disposal, from 0.17 MJ/m^2 (2013 base case) to zero (high recycling case).

Fig. 2.4. Primary energy use per square meter of plasterboard consumed

There are no savings on the total energy use when moving from the 2013 base case towards the high recycling case. Overall, 568.34 TJ increase of primary energy per year result as a consequence of increases in transport of post-consumer plasterboard waste to the recycling facility and transport of recycled gypsum to the manufacturing plant.

Fig. 2.5. Primary energy use in TJ per year within the EU-27 plasterboard life cycle.

2.3.3. GHG emissions implications

The potential contribution of different plasterboard recycling scenarios to the global warming impact category, expressed as CO₂ equivalents, is estimated by quantifying all significant GHG emissions and removals over the product's life cycle (ISO, 2013) in the three scenarios, as presented in Fig. 2.6 and Fig. 2.7.

Fig. 2.6. GHG emissions per square meter of plasterboard consumed

GHG emitted from raw material supply to plasterboard production stages (modules A1 – A3 according to EN 15804) equals 2.05 kg CO₂ eq in the 2013 base case, and 2.06 kg CO₂ eq in the high recycling case, per square meter of plasterboard. This minor difference means that decreased emissions derived from gypsum mining and transport of natural gypsum in the high recycling case are almost balanced by the increased emissions from the pre-processing stage. The variations of the cradle-to-cradle lifecycle emissions are higher when moving from the 2013 base case (2.45 kg CO₂ eq/m²) towards the high recycling case (2.23 kg CO₂ eq/m²). Overall, the total GHG emission is 9% smaller in the high recycling case. GHG emissions are slightly greater in the processes of transport of recycled gypsum, pre-processing stage, transport of plasterboard waste to recycling and waste processing. Such emissions are lower for gypsum mining, transport of natural gypsum and final disposal. The latter emissions from landfill have a decisive contribution to the final result, due to methane released from degradation of facing paper. This biogenic emission constitutes 94% of the emissions in the final disposal stage and 10% of the total life cycle emissions.

Fig. 2.7. GHG emissions, in kt of CO₂ eq per year, of the EU-27 plasterboard life cycle

2.3.4. Sensitivity analysis

Here the effect of variation of input parameters on the two metrics previously modelled is explored: primary energy use (MJ/m²) and GHG emissions (kg CO₂ eq/m²). Table 2.5 summarizes the results of the sensitivity analysis performed on three criteria: C&D waste generated, transport and plasterboard final disposal.

Only those parameters that exceed an effect of 1% change on the life cycle of plasterboard are included in the sensitivity results. Generally, the sensitivity variation is symmetric, varying uniformly in the positive and negative direction. The GHG emissions derived from final disposal vary by 2% as the post-consumer plasterboard waste generated changes from 1.90 to 1.52 and 2.28 Mt. Increase of the case A natural gypsum weighting factor by 10% results in 2% reduction in total primary energy and 1% reduction in GHG emissions. Variation of the transport to building site to 152 km reduces the primary energy demand and GHG emissions by 2 and 1% respectively. Landfill gas collection efficiencies have been typically estimated to be in the range of 50-75% (Spokas et al., 2006). Reduction of the assumed collection efficiency of landfill gas from 75% down to 50%, increases the total biogenic emissions released by 9% compared to the reference scenario. In addition, if plasterboard is deposited in a monocell landfill instead of a mixed-waste landfill, the CH₄ emissions associated with paper degradation are assumed to be zero, as the amount of methane produced in monocells is small and released at a low rate, thus undergoing oxidation to carbon dioxide in the surface layers of the site before it could be released into the atmosphere (WRAP, 2008). This change in the type of disposal results in a 10% decrease of total GHG emissions. Thus, CH₄ emissions coming from paper content degradation make a significant difference in the total GHG emissions, as a function of the landfill type and gas recovery infrastructure.

Table 2.5. Effect of varying parameters in the primary energy use and GHG emissions over the life cycle of plasterboard. Ref: reference. PB: plasterboard. Values in the columns termed as “Base case” correspond to the 2013 base case results.

Parameter	Reference condition	New condition	PE (MJ/m ²)		GHG (kg CO ₂ eq/m ²)	
			Base case	Change from ref	Base case	Change from ref
<i>C&D waste generation</i>						
Post-consumer plasterboard waste (Mt)	1.90	-20%	43.02	-0.07	2.39	-0.06
Post-consumer plasterboard waste (Mt)	1.90	+20%	43.16	0.07	2.50	0.06
<i>Transport</i>						
Natural gypsum, weighting factor case A (%)	0.87	0.97	42.23	-0.86	2.43	-0.02
Plasterboard to building site (km)	189.64	-20%	42.05	-1.04	2.42	-0.03
Plasterboard to building site (km)	189.64	+20%	44.12	1.04	2.48	0.03
<i>Final disposal</i>						
Collection efficiency of landfill gas (%)	0.75	0.50	43.09	0.00	2.67	0.22
Disposal in monocell landfill - CH ₄ (kg/t PB deposited)	4.48	0.00	43.09	0.00	2.21	-0.24

2.4. Conclusions

This paper presents quantitative scenario modelling of gypsum plasterboard recycling in the EU-27. A life cycle model is the basis of the assessment, from which the known mass flows are quantified, using principles of mass balance to determine flows of other materials, e.g. facing paper or post-consumer plasterboard waste. Based on these system-wide mass flows, energy and GHG intensity factors are applied to each process to estimate total life cycle energy use and GHG emissions.

Representative scenarios are defined (“Zero recycling case”, “2013 base case”, “High recycling case”) and different assumptions based on LCI references (e.g. transport distances travelled) are considered, with the aim of evaluating the impact of different levels of recycled gypsum reincorporated in the manufacturing process (0%, 5%, 18.7%, respectively).

The main conclusions that can be drawn from this investigation are:

- The composition by weight percentage of the resulting three plasterboards show that natural gypsum comprises around 68% in the zero recycling case, decreasing to 63% in the 2013 base case and 49% in the high recycling case.
- In the 2013 base case, 5% recycled gypsum content in new plasterboard corresponds to 6.4% plasterboard waste recycled into plasterboard (closed-loop recycling). In the zero recycling case, all plasterboard waste is either landfilled (93.6%) or utilised for other uses (6.4%). In the high recycling case, 18.7% of recycled gypsum is reincorporated, corresponding to 93.6% closed-loop plasterboard recycling.
- When moving from the 2013 base case to the high recycling case, 1.65 Mt/year of plasterboard waste landfilling is avoided, therefore contributing to mitigating primary resource depletion and preventing H₂S and CH₄ emissions from landfills.

- Reincorporating greater amounts of recycled gypsum results in higher overall primary energy use. However, the difference between the scenarios is very minor: 43.09 MJ/m² in the zero recycling and 2013 base cases and 43.62 MJ/m² in the high recycling case.
- The potential contribution of different plasterboard scenarios to global warming, expressed as CO₂ equivalents, result in greater differences: 2.53 kg CO₂ eq/m² in the zero recycling case, 2.45 kg CO₂ eq/m² in the 2013 base case and 2.23 kg CO₂ eq/m² in the high recycling case. Biogenic emissions from paper degradation in the end-of-life stage, which are dependent on landfill type and infrastructure, are primary drivers of the difference between total GHG emissions in the different scenarios.
- For both primary energy use and GHG emissions, when moving from the zero recycling case towards the high recycling case, greater impacts occur in the processes of transport of recycled gypsum, pre-processing stage, transport of plasterboard waste to recycling and waste processing, while lower impacts are observed in gypsum mining, transport of natural gypsum and final disposal.
- The representative scenarios incorporate assumptions in an attempt to communicate relevant results for the EU average plasterboard. For plasterboards with parameters that deviate from this average, different results may apply.

References

- Antink, R., Garrigan, C., Bonetti, M., & Westaway, R. (2014). Greening the Building Supply Chain. UNEP Sustainable Buildings and Climate Initiative. United Nations Environment Programme. Job Number: DTI/1753/PA. Retrieved 17 January 2016, from http://www.unep.org/sbci/pdfs/greening_the_supply_chain_report.pdf
- Bojić, M., Djordjević, S., Stefanović, A., Miletić, M., & Cvetković, D. (2012). Decreasing energy consumption in thermally non-insulated old house via refurbishment. *Energy and Buildings*, 54, 503–510. <http://doi.org/10.1016/j.enbuild.2012.03.045>
- Construction Recycling Initiative (CRI) - National Capital Region. (2010). GYPSUM Recycling in the National Capital Region. Position Paper.
- Dodoo, A., Gustavsson, L., & Sathre, R. (2010). Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard. *Resources, Conservation and Recycling*, 54(12), 1152–1160. <http://doi.org/10.1016/j.resconrec.2010.03.010>
- Doka, G. (2003). Life Cycle Inventories of Waste Treatment Services. ecoinvent report No. 13. Part V. Building Material Disposal. Final report of the project of a National Life Cycle Inventory Database 'ecoinvent 2000' commissioned by BUWAL/BFE/ASTRA/BLW. Dübendorf.
- ECOPA - European Coal Combustion Products Association. (2010). Production and Utilisation of CCPs in 2010 in Europe (EU 15). Retrieved 17 January 2016, from <http://www.ecoba.com/ecobaccpprod.html>
- Ecoinvent. (2012). Ecoinvent v2.2 Life Cycle Inventory (LCI) database, Gypsum, mineral, at mine/CH S. Retrieved 5 June 2015, from <http://www.ecoinvent.org/>
- Emery, S. B., Smith, D. N., Gaterell, M. R., Sammons, G., & Moon, D. (2007). Estimation of the recycled content of an existing construction project. *Resources, Conservation and Recycling*, 52(2), 395–409. <http://doi.org/10.1016/j.resconrec.2007.03.009>
- EPA's Waste Reduction Model (WARM). (2014). WARM Version 13 - Drywall.
- Eurogypsum. (2010). European Life Cycle Assessment on Plasterboard: European Environmental Declaration – Explanatory Note.

- European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Towards a circular economy: A zero waste programme for Europe (2014).
- European Commission. Proposal for a Directive of the European Parliament and the Council (2014).
- European Commission (DG ENV). (2011). Service Contract on Management of Construction and Demolition Waste - SR1. Final Report Task 2. A project under the Framework contract ENV.G.4/FRA/2008/0112. Retrieved 17 January 2016, from http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf
- European Commission DG Environment. (2010). Green Public Procurement Wall Panels Technical Background Report.
- European Commission Joint Research Centre - European reference Life-Cycle Database. (2007). Process data set: Gypsum plasterboard (03.00.000). Gypsum plasterboard;technology mix of plasterboard production;production mix at factory;12.5 mm thick, 10kg/m2. Retrieved 17 January 2016, from <http://eplca.jrc.ec.europa.eu/ELCD3/showProcess.xhtml?sessionId=2703835E85D137D1E5882A56E8BBD0C6?uuid=cc39e70e-4a40-42b6-89e3-7305f0b95dc4&version=03.00.000>
- European Environment Agency. (2011). Specific CO₂ emissions per tonne-km and per mode of transport in Europe, 1995-2011 — European Environment Agency (EEA). Retrieved 17 January 2016, from <http://www.eea.europa.eu/data-and-maps/figures/specific-co2-emissions-per-tonne-2>
- European Environment Agency (EEA). (2008). Trends in energy GHG emission factors and % renewable electricity (EU-27). Retrieved 17 January 2016, from <http://www.eea.europa.eu/data-and-maps/figures/trends-in-energy-ghg-emission>
- Eurostat. (2012). Generation of waste, NACE Rev. 2. Code F, Construction. Total Waste. 2012. Last update: 23-07-2015. Retrieved 4 April 2016, from <http://ec.europa.eu/eurostat>
- Eurostat - Prodcom. (2013a). NACE Rev. 2. Statistics on the production of manufactured goods, total volume annual. 2013. Retrieved 4 April 2016, from <http://ec.europa.eu/eurostat/web/prodcom>
- Eurostat - Prodcom. (2013b). PRODCOM ANNUAL TOTAL (NACE Rev.2). PRCCODE: 08112030.
- Govindan, K., Soleimani, H., & Kannan, D. (2014). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research*, 240(3), 603–626. <http://doi.org/10.1016/j.ejor.2014.07.012>
- GtoG project. (2013a). Life+ Gypsum to Gypsum (GtoG) project 'From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry' LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4191
- GtoG project. (2013b). DA1: Inventory of current practices LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from <http://gypsumtogypsum.org/documents/deliverable-a1-report-on-current-practices.pdf>
- GtoG project. (2015). DC1. Report on best practice indicators for deconstruction, recycling and reincorporation LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/news/newsarchive2015/documents/20150715_gtog.pdf
- Herrero, M. J., Escavy, J. I., & Bustillo, M. (2013). The Spanish building crisis and its effect in the gypsum quarry production (1998–2012). *Resources Policy*, 38(2), 123–129. <http://doi.org/10.1016/j.resourpol.2013.02.005>
- International Energy Agency. (2008). *Worldwide Trends in Energy Use and Efficiency. Key Insights from IEA Indicator Analysis*. Paris: IEA Publications.
- International Standard. (1999). ISO 14021:1999/Amd 1:2011. Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling). Amendment 1.
- International Standard. ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework (2006).

- International Standard. ISO 14044:2006. Environmental management - Life cycle assessment - Requirements and guidelines (2006).
- IPCC. (2013). Fifth Assessment Report - Climate Change. Retrieved from <http://www.ipcc.ch/report/ar5/wg1/>
- ISO. (2013). ISO/TS 14067:2013. Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication.
- Kourmpanis, B., Papadopoulos, a., Moustakas, K., Stylianou, M., Haralambous, K. J., & Loizidou, M. (2008). Preliminary study for the management of construction and demolition waste. *Waste Management & Research*, 26(3), 267–275. <http://doi.org/10.1177/0734242X07083344>
- OSHA Occupational Safety and Health Administration. US Department of Labor. (2005). Hydrogen Sulfide OSHA FactSheet. DSG 10/2005. Retrieved 17 January 2016, from https://www.osha.gov/OshDoc/data_Hurricane_Facts/hydrogen_sulfide_fact.pdf
- Plimmer, B., Davies, S., & Carter, L. (2007). Report on Life Cycle Assessment of Plasterboard PBD014, Landfill Emissions Inventory 07514290064.500.
- Roskill. (2014). Gypsum and Anhydrite: Global Industry Markets and Outlook (Eleventh).
- Spokas, K., Bogner, J., Chanton, J. P., Morcet, M., Aran, C., Graff, C., ... Hebe, I. (2006). Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems? *Waste Management*, 26(5), 516–525. <http://doi.org/10.1016/j.wasman.2005.07.021>
- Tam, V. W. Y., Fung, I. W. H., Sing, M. C. P., & Ogunlana, S. O. (2014). Best practice of prefabrication implementation in the Hong Kong public and private sectors. *Journal of Cleaner Production*. <http://doi.org/10.1016/j.jclepro.2014.09.045>
- The Council of the European Union. (2003). Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex to Directive 1999/31/EC (2003/33/EC). *Official Journal of the European Communities*, L 11/27-11/49.
- U.S. Geological Survey - USGS. (2013). Minerals Information - Gypsum Statistics and Information. Retrieved 17 January 2015, from <http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/>
- United States Environmental Protection Agency EPA. (2015). Landfilling. Retrieved 17 January 2016, from <http://www3.epa.gov/epawaste/conservation/tools/warm/pdfs/Landfilling.pdf>
- Venta, G. J. (1997). Life cycle analysis of gypsum board and associated finishing products.
- Villoria Sáez, P., del Río Merino, M., Porras-Amores, C., & San-Antonio González, A. (2014). Assessing the accumulation of construction waste generation during residential building construction works. *Resources, Conservation and Recycling*, 93, 67–74. <http://doi.org/10.1016/j.resconrec.2014.10.004>
- Williams, B. (2008). Europroms PRODCOM Data, User Guide, 1–18.
- WRAP and Environmental Resources Management Ltd (ERM). (2008). Technical Report: Life Cycle Assessment of Plasterboard.
- WRAP, & BSI. (2013). PAS 109:2013. Specification for the production of reprocessed gypsum from waste plasterboard. Retrieved 4 May 2016, from [http://www.wrap.org.uk/sites/files/wrap/PAS109 \(2013\).pdf](http://www.wrap.org.uk/sites/files/wrap/PAS109%20(2013).pdf)
- Xu, Q., & Townsend, T. (2014). Factors affecting temporal H₂S emission at construction and demolition (C&D) debris landfills. *Chemosphere*, 96, 105–11. <http://doi.org/10.1016/j.chemosphere.2013.07.052>

3 FACTORS INFLUENCING POST-CONSUMER GYPSUM RECYCLING

CHAPTER OVERVIEW

This chapter identifies factors for the success of gypsum recycling and investigates stakeholder's views on the factors. The method includes a study of the literature and a structured questionnaire distributed to stakeholders. Data analysis is used to rank the critical factors (CFs) and conduct a comparison of respondents views divided into two groups (gypsum recycling and non-gypsum recycling countries are differentiated).

Published as

Jiménez Rivero, A., García Navarro, J., 2017. Exploring factors influencing post-consumer gypsum waste recycling and landfilling in the European Union. *Resources, Conservation and Recycling*, 116, 116-123. DOI: <http://dx.doi.org/10.1016/j.resconrec.2016.09.014>.

Main research questions addressed and relation to other chapters

	Research question (and related specific objective in parentheses)	Brief answer and → Relation with other chapters
<div> <div>Chapter 1. Gypsum waste generation and management</div> <div>Chapter 2. Life cycle energy and material flows</div> <div>Chapter 3. Factors influencing post-consumer gypsum recycling</div> <div>PART II: MACRO-LEVEL</div> </div>	What factors influence gypsum recycling in the EU? (O3)	<p>15 factors are identified as critical for gypsum recycling. Examples include “Landfill ban” (CF1) and “Environmental taxes” (CF2). More than half of the factors belong to the policy domain, which indicates the relevance of policy instruments for promoting a circular economy for gypsum products.</p> <p>→ Chapter 1 and Chapter 2 provided the basis for the formulation of this Chapter. On the one hand, Chapter 1 showed that only half of the studied countries currently recycle post-consumer GW. On the other hand, Chapter 2 estimated the total amount of post-consumer GW landfilled in 2013, which equals to 87.2%.</p> <p>→ In contrast with practices adopted by the value chain operators (in Chapter 6), factors cannot be directly controlled by individuals. Both of them (practices and factors) determine the fate of GW and might be mutually beneficial.</p>
<div> <div>Chapter 4. Physical and mechanical characterization</div> <div>Chapter 5. End-of-life case studies analysis</div> <div>Chapter 6. Best practices in the end-of-life stage</div> <div>PART III. MICRO-LEVEL</div> </div>		

3.1. Introduction

Although certain factors can determine more favourable destinations, post-consumer construction products (also termed as construction and demolition (C&D) waste) are typically disposed of in landfills in most of the EU-28 countries (European Commission, 2011). Higher options in the priority order include reusing, recycling and recovery operations, following the waste hierarchy (European Parliament and the Council of the European Union, 2008). Nonetheless, a few European countries have already managed to divert high rates of waste from landfills. Examples include Denmark, the Netherlands, and the UK (European Commission, 2011).

Inert and non-inert C&D waste can be distinguished, each of whom possess particular recovery operations with diverse environmental implications. An example of non-inert waste is gypsum. Besides contaminating recyclable inert waste, gypsum waste (GW) has special requirements to be disposed in landfills (The Council of the European Union, 2003). What is more, GW ends up in landfills in 20 out of the 28 European countries (Jiménez Rivero, De Guzmán Báez, & García Navarro, 2015), not always in “landfills for non-hazardous waste in cells where no biodegradable waste is accepted” (hereinafter referred to as “monocell landfill”), as established in the Council Decision 2003/33/EC, as a consequence of a range of factors that affect this fate.

Post-consumer GW represents a small percentage of the total C&D waste, but the potential impacts on the environment can be quantified as follows. A total of 1.9 million tonnes were estimated to be generated in 2013 in the EU-27, which equals to 0.23% of the total C&D waste (Jiménez Rivero, Sathre, & García Navarro, 2016). Two main undesirable effects are produced when gypsum is not managed appropriately. First, gypsum contaminates concrete for recycling due to its sulphate content (Barbudo et al., 2012), mainly when all waste streams are treated as mixed C&D waste. Second, diversion of GW from landfills avoids potential landfill emissions, enhances resource efficiency and contributes to meeting the European target on C&D waste recovery (European Parliament and the Council of the European Union, 2008). For example, 13.5% kg CO₂eq/m² were estimated to be avoided when moving from a zero to a high recycling case (0 and 93.6% of gypsum plasterboard being recycled, respectively) (Jiménez Rivero et al., 2016).

Although gypsum recycling holds the potential for avoiding gypsum landfilling, it is estimated that currently only six per cent of post-consumer gypsum close the material loop in a circular economy, being the rest downcycled or landfilled (Jiménez Rivero et al., 2016). Gypsum recycling (GR) countries include France, Benelux (Belgium, the Netherlands, and Luxembourg), Finland, the UK, Denmark, and Sweden (Jiménez Rivero et al., 2015). Therefore, the rest of non-gypsum recycling (NGR) countries lead the current scene. Two key conditions enable the production of quality recycled gypsum (RG) (in compliance with the RG quality criteria as detailed in GtoG project (2015a)): the implementation of building deconstruction and the existence of recycling facilities following the relevant quality criteria. For these conditions to be met, a number of factors are influential. Understanding what factors lead to achieve these conditions becomes vital to perform sustainable waste management practices and increase the use of recycled gypsum.

The term “factor” can be defined as “something that helps produce or influence a result: one of the things that cause something to happen” (Merriam-Webster, 2015). A number of authors have investigated factors and measures that influence more sustainable approaches in C&D waste management. The focus remains on construction and renovation works in Asia, Oceania and some regions of Europe. For example, Tam & Tam (2006) outlined recommendations to improve the implementation of waste management in Hong Kong. In this region also, factors that hinder the implementation of a waste management plan were explored by Tam (2008). Factors influencing attitudes, behaviours and perceptions on waste management have also been examined from district perspectives: Begum et al. (2009) focused on contractors in Malaysia, Teo & Loosemore (2001) surveyed construction workers in Australia and Kulatunga et al. (2006) focused on workers in Sri Lanka. Other authors have identified critical factors (CFs) for different processes and works (Li & Yang, 2014; Lu & Yuan, 2010; Wang et al. 2010), specifically for C&D waste management in China (Lu & Yuan, 2010), on-site sorting of construction waste in China (Wang et al., 2010) and office building retrofit projects in Australia (Li & Yang, 2014). In the form of measures, Yuan (2013) discussed management measures that contribute to effective construction waste management in China. Regarding on-site management factors, Ya’cob et al. (2013) surveyed contractors in Malaysia. More recently, Ajayi et al. (2015) explored factors, practices and strategies to achieve effective waste management in the UK context.

The specific objective of this study is to analyse the factors influencing gypsum recycling and landfilling in the European Union. Section 2 is concerned with the methodology used, including the selection of potential factors from the literature (see Section 2.1). Section 3 presents and discusses findings from the data analysis, which reveals CFs categorised into four domains: policy, economic, social, and environmental aspects. It is worth noting that some of the factors are interrelated and might influence each other. For example, the “Recycler’s gate fee” (identified as CF6 in Section 3.3 et seq.) may vary with the “Price of the recycled gypsum (RG)” (identified as CF3 in Section 3.3 et seq.). These connections are explained, along with the description of each factor, in Sections 3.1 and 3.2.

The present study complements the already started analysis on gypsum recycling in the EU-28, framed in the European Life+ Gypsum to Gypsum project “From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry” (GtoG project, 2013a). First, a report on current practices on gypsum recycling in Europe was drafted (GtoG project, 2013b). Then, five case studies were monitored between 2014 and 2015 (covering deconstruction of gypsum-based systems, processing of GW and reincorporation of RG). As a result, the ideal conditions to produce RG from end-of-life gypsum were formulated (Jiménez-Rivero & García-Navarro, 2016). Best practices for the management of gypsum were then proposed (GtoG Project, 2015b). These practices aim to ensure quality recycled gypsum, and they are based on best techniques and technology in gypsum recycling countries, supported by the monitoring and analysis conducted in the GtoG pilot projects. Examples of best practices are “Perform on-site segregation of GW” and “Set clear RG quality criteria”. The main aspect differentiating factors from practices is the level of analysis. While best practices focus at the micro-level (i.e. a particular deconstruction-recycling value chain) factors are applicable at the macro-level (e.g. EU-28 or a EU country). In contrast with practices adopted by the value chain

operators, factors cannot be directly controlled by individuals. Both of them (practices and factors) determine the fate of GW and might be mutually beneficial. For instance, implementing best practices can promote mutual trust between agents

This investigation brings together, for the first time, factors influencing the emerging market for post-consumer RG. These include factors previously considered by EU institutions, public bodies, international organisations and EU research projects (Section 2.1). The identified factors are thus considered representative at EU level.

3.2. Method

Inspired by the critical success factor approach, the method is divided into three phases: selection of factors, stakeholders' consultation and data analysis. This approach was first used by Rockart (1979) and recently adopted to investigate critical factors and best practices in C&D waste (Lu et al., 2008; Villoria Saez et al., 2013; Wang et al., 2010).

3.2.1. *Selected factors for the success of gypsum recycling*

Factors for the success of gypsum recycling were identified from the literature as shown in Table 3.1, and adapted to the case of GW when required. The time period of study resulted from the published literature on the topic, which was found to be the 1998-2016 period. Additional factors were defined as a result of findings from the GtoG project, which framed this investigation.

Table 3.1. Factors for the success of gypsum recycling

Factors	Source
Availability of natural and/or FGD gypsum	European Commission (2011), Yuan et al (2011), Jiménez Rivero et al. (2016)
Awareness of the impacts of gypsum landfilling and gypsum recycling	Teo & Loosemore (2001), Klang et al. (2003), Lu & Yuan (2010), Ya'cob et al. (2013), Yuan (2013), Ajayi et al. (2015), European Commission (2015), Lieder & Rashid (2015), Jiménez Rivero et al. (2016)
Building rating tools	Antink et al. (2014), Oyedele et al. (2014), Ajayi et al. (2015)
Collaboration between stakeholders	Lönngren et al. (2010), Department for Environment Food and Rural Affairs - defra and the Plasterboard Sustainability Partnership - psp (2013), European Commission (2014), Ajayi et al. (2015)
Environmental taxes (landfill tax)	Morris et al. (1998), Klang et al. (2003), OECD (2003), Duran et al. (2006), Fischer et al. (2012), Watkins et al. (2012), Garbarino & Blengini (2013), Scharff (2014), WRAP (2014), Ajayi et al. (2015), European Commission (2015)
Green public procurement criteria	OECD (2003), Garbarino & Blengini (2013), GtoG project (2013b), Antink et al. (2014), European Commission (2015)

Landfill ban	OECD (2003), WRAP (2012), Finnveden et al. (2013), Scharff (2014)
Landfill operation cost	Eurogypsum (2007), European Commission (DG ENV) (2011), Environment Agency (2012), GtoG project (2013b)
Legal alternative destinations that do not favour the options that are higher in the waste hierarchy	GtoG project (2013b)
Legal status of GW (end-of-waste status)	Delgado et al. (2009), WRAP & Environment Agency (2013), GtoG Project (2013b), Garbarino & Blengini (2013), Jiménez Rivero et al. (2015), GtoG project (2015b)
Objectives and targets on waste management	De Minister van Volkshuisvesting et al (2008), Les Industries du Plâtre (2008), Department for Environment Food and Rural Affairs - defra and the Plasterboard Sustainability Partnership - psp (2013)
Other levies and fines	OECD (2003), Garbarino and Blengini (2013), Seror et al. (2014)
Price of the RG	OECD (2003), Field & Sroufe (2007), GtoG project (2013b), Oyedele et al. (2014)
Recycler's gate fee	GtoG project (2015b)
Regulatory framework favouring building deconstruction	OECD (2003), Couto & Couto (2010), CIB International Council for Research and Innovation in Building and Construction (2014), European Commission (2014)
Regulatory framework favouring pre-deconstruction audit	GtoG project (2013b), Deloitte (2015), European Commission (2014)
Regulatory framework favouring SWMP	Tam (2008), Couto & Couto (2010)
Regulatory framework favouring the use of recycled materials	OECD (2003), European Commission (2014), Deloitte (2015)
Strategy of the gypsum recycler (sources, brands or type of board accepted)	GtoG project (2013b)
Waste management software solutions	Cheng & Ma (2013), Ajayi et al. (2015), Akinade et al. (2015), Deloitte (2015)

GW: gypsum waste; RG: recycled gypsum; SWMP: site waste management plan

3.2.2. Stakeholders' consultation

A questionnaire was used to investigate stakeholders' views on the factors influencing the success of gypsum recycling. 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. In this meeting, the consultation strategy was also defined (i.e. GtoG partners in charge of translating the questionnaire 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). Space was provided to accommodate comments. The questionnaire also contained a general data part (see Appendix 2). A 38% response rate was achieved.

A total of 58 responses ($N=58$) were gathered. These stakeholders included manufacturers, construction agents, waste collectors and gypsum recyclers as well as other stakeholders (researchers and public institutions and associations). Responses from some countries could not be gathered (e.g. Poland) or were limited (e.g. Denmark). Therefore, responses were analysed per group of countries. Two groups were considered: gypsum recycling (GR) and non-gypsum recycling (NGR) countries. While 62% of the stakeholders ($N=36$) perform their activity in GR countries (Belgium, Denmark, France, the Netherlands, and United Kingdom), 48% ($N=22$) work in NGR countries (Austria, Germany, Greece, Portugal and Spain). Respondents working at European level were considered in the GR countries group. All responses from the GR group come from countries in which end-of-life gypsum has started to be recycled (i.e. Belgium, France, the Netherlands, the UK and Scandinavia according to the report GtoG project (2013b)). Further details on the break down per country and per activity can be found in the Appendix 2.

3.2.3. Data analysis

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 ($\alpha=0.05$). Moreover, Cronbach's alpha coefficient was assessed to check the internal consistency of the scale. The alpha value was 0.903. As this value is above 0.8, the scale can be considered reliable with our sample (Carmines & Zeller, 1979).

The CFs were ranked according to their mean value (M), an approach commonly adopted in construction management research to evaluate Likert-type scales (Ali, Al-Sulaihi, & Al-Gahtani, 2013; Lu & 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 y th score (S_y) for the x th factor and S_y is the score given by stakeholders for each factor. The cut-off mean value was set at 4.00 to be selected as a CF, as 4.00 in the 5-point Likert-type scale denotes "important", recognized by value chain operators in GR countries as current leading approaches, built on their experience.

CFs are categorized based on the analysis performed by OECD (2003), where policy instruments are labelled as regulatory, economic and information tools. Three additional domains are taken considering the triple bottom line: economic, social, and environmental aspects. As Lieder & Rashid (2015) found in the recent review on the circular economy concept, business and economic perspectives have been traditionally neglected while studying the circular economy (Lieder & Rashid, 2015).

3.3. Results and discussion

Table 3.2. summarizes the analysis on the importance given by stakeholders to the selected factors (see Section 2.3 for details on the selected statistics). CFs are ranked (from the highest to the lowest mean) according to the mean value from GR countries, due to their experience in the achievement of an improved deconstruction-recycling value chain. The higher the mean value, the higher the stakeholders valued the factor. 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 NGR countries view the CFs.

Table 3.2. Results of the questionnaire survey on the factors influencing gypsum recycling

Domain	Factor	GR countries		NGR countries		Mann-Whitney		CF
		M	SD	M	SD	Z	p	
Policy	Landfill ban	4.53	0.61	4.24	1.00	-0.99	0.324	CF1
Policy	Environmental taxes (landfill tax)	4.51	0.89	4.30	0.98	-1.16	0.247	CF2
Economic	Price of the RG	4.45	0.72	4.57	0.68	-0.63	0.531	CF3
Environmental	Availability of natural and/or FGD gypsum	4.39	0.79	4.10	1.02	-1.00	0.319	CF4
Social	Awareness of the impacts of gypsum landfilling and gypsum recycling	4.34	0.76	3.36	1.09	-3.46	0.001	CF5
Economic	Recycler's gate fee	4.31	0.87	4.28	0.57	-0.71	0.476	CF6
Economic	Landfill operation cost	4.29	0.80	4.05	1.08	-0.66	0.509	CF7
Social	Objectives and targets on waste management	4.26	0.78	3.64	1.26	-1.85	0.065	CF8
Policy	Regulatory framework favouring the use of recycled materials	4.26	0.85	4.33	0.73	-0.17	0.861	CF9
Policy	Regulatory framework favouring building deconstruction	4.24	0.82	4.19	0.93	-0.06	0.955	CF10
Social	Collaboration between stakeholders	4.23	0.88	3.36	1.05	-3.05	0.002	CF11
Policy	Green public procurement criteria	4.16	0.81	3.86	1.01	-1.02	0.308	CF12
Policy	Legal alternative destinations that do not favour the options that are higher in the waste hierarchy	4.13	0.94	3.33	1.19	-2.37	0.018	CF13
Policy	Other levies and fines	4.00	0.94	4.25	0.79	-0.89	0.375	CF14
Policy	Regulatory framework favouring SWMP	4.00	0.98	3.55	1.43	-0.90	0.367	CF15
Policy	Legal status of GW (end-of-waste status)	3.97	1.17	3.81	1.17	-0.59	0.554	
Policy	Regulatory framework favouring pre-deconstruction audit	3.94	0.98	3.71	1.35	-0.35	0.724	

Economic	Strategy of the gypsum recycler (sources, brands or type of board accepted)	3.85	1.12	3.37	0.96	-1.67	0.095
Environmental	Building rating tools	3.67	1.05	3.73	0.94	-0.27	0.790
Environmental	Waste management software solutions	3.42	1.09	2.86	1.20	-1.60	0.110

3.3.1. Policy domain

Fig. 3.1 shows complementary graphical representations of the critical policy instruments. The left part illustrates the calculated rate of respondents choosing a particular score (5=extremely important, 4=important, 3=neutral, 2=unimportant, 1=negligible). The right part displays the comparison of the mean rank between GR and NGR countries.

Fig. 3.1. Additional analysis on the factors part of the policy domain. Breakdown into respondents' rate (left) and group of countries (right). GR countries: BE, UK, FR, NL, DK. NGR countries: AU, DE, GR, SP, PT. GPP: green public procurement

— Regulatory instruments

CFs that fall into regulatory aspects encompass “Landfill ban” (CF1), “Regulatory framework favouring the use of recycled materials” (CF9), “Regulatory framework favouring building deconstruction” (CF10), “Legal alternative destinations that do not favour the options that are higher in the waste hierarchy” (CF13), and “Framework favouring SWMP” (CF15) (see Table 3.2).

“Landfill ban” (CF1) ranked first regarding the contribution to building a circular economy around gypsum. In particular, 91% of stakeholders considered that CF1 is an important or extremely important factor towards that end (see Fig. 3.1). This might be due to the potential of landfill bans on diverting waste from landfills. As the incineration of gypsum waste typically affects emissions because of its sulphate content (Eurogypsum, 2007), a ban would be likely to move the waste from disposal to recycling, which implies two steps up in the waste hierarchy. An alternative option would be to promote “Compulsory recycling of recyclable materials” (Finnveden et al., 2013).

As WRAP recently warned, restrictions on landfill may entail fly-tipping and illegal exports (WRAP, 2012). Legal exports might also fail to contribute to a circular economy, destination included within the

CF13 “Legal alternative destinations that do not favour the options that are higher in the waste hierarchy”. For instance, the export of waste might be considered a recovery operation under certain conditions, being the waste disposed of in “underground storage” in other country (Scharff, 2014). As for the case of gypsum, exports for backfilling operations have been already observed (European Commission (DG ENV), 2011). In order to prevent such alternative destinations that do not favour the waste hierarchy, instruments such as mandatory reporting and demolition permissions can be put in place (see OECD, 2003 for further information). The Mann-Whitney U-test revealed significant difference in the way GR and NGR stakeholders rate this factor, being CF13 the least valued CF in NGR countries (see Table 3.2, $p < 0.05$). This difference can be explained by the limited experience in the circular economy principles in these contexts.

A “Regulatory framework favouring the use of recycled materials” (CF9) and a “Regulatory framework favouring building deconstruction” (CF10) were similarly rated by GR and NGR countries (see Fig. 3.1). It should be noted that construction agents might not always perceive deconstruction as a favourable means for a circular economy, as higher associated costs are commonly reported owing to additional time and labour needed when compared to traditional demolition (Coelho & de Brito, 2011; Dantata, Touran, & Wang, 2005; Pacheco-Torgal, Tam, Labrincha, Ding, & Brito, 2013). Nevertheless, building deconstruction enables maximum recovery of resources from end-of-life products (Jiménez-Rivero & García-Navarro, 2016), being a key condition for enabling gypsum recycling (see “Introduction” section). Moreover, deconstruction may provide economic benefits from the landfill cost avoided (see “Landfill tax” (CF2) in “Economic and general policy instruments” section and “Landfill operation cost” (CF7) in “Economic domain” section), compared to conventional demolition practices (Rodríguez-Quijano, Jiménez-Rivero, de Guzmán-Báez, & García-Navarro, 2015).

On the other hand, a regulatory framework favouring the site waste management plan (CF15) was the least valued CFs, being particularly low the mean scores of the NGR countries. A possible explanation relates to the perception of a SWMP as extra paperwork (Department for Environment Food and Rural Affairs - defra, 2013) or as difficult to implement, due to reasons such as “Low economic incentive”, “Increase in overhead cost” or “Complicated subcontracting system” (Tam, 2008). Similarly, Ajayi et al. (2015) found a number of limitation to the effectiveness of a SWMP (e.g. “It requires additional man-hours/specialist”). Nevertheless, SWMPs involve multiple potential benefits, including waste prevention and management strategies before, during and after the construction works (Ajayi et al., 2015).

— Economic and general policy instruments

The CFs falling into this category are related to economic instruments and information tools. Economic instruments involve “Landfill tax” (CF2) and “Levies and fines” (CF13). On the other hand, “Green Public Procurement criteria” (CF12) is considered to be a general policy instrument (OECD, 2003).

A “Landfill tax” (CF2) or levy was viewed as important or extremely important by 89% of respondents (see Fig. 3.1). Such environmental tax has also recently been identified as a crucial economic parameter for gypsum recycling (GtoG project, 2013b; Rodríguez-Quijano et al., 2015). Moreover, high landfill

taxes produced cost savings in five case studies on the deconstruction-recycling value chain (Jiménez-Rivero & García-Navarro, 2016). Furthermore, the effectiveness of this instrument for the reduction of landfill disposal has been demonstrated through case studies in Denmark, the Netherlands and the UK (OECD, 2003), countries in which a market for recycled gypsum exists (GtoG project, 2013b). More recently, Scharff (2014) emphasized the role of the landfill tax in achieving low landfill rates in the Netherlands. Likewise, Garbarino & Blengini (2013) highlighted the effect of increased landfill cost as relevant in the development of gypsum recycling practices.

Besides the landfill tax (CF2), the factor “Other levies and fines” (CF14) was perceived as important for closing the loop on gypsum, being one of the most valued CF in NGR countries (see Table 3.2). These instruments may raise awareness among stakeholders and thus help to manage C&D waste (Ajayi et al., 2015). In building construction, other levies relate to the use of natural or virgin materials (e.g. “Aggregate levy” in the UK) and the control of excavation or gravel extraction (OECD, 2003). For its part, fines or penalties on landfill can discourage fly-tipping when sanctions are actually applied and hence the level of awareness is raised (Seror et al., 2014).

As regards other general policy mechanisms, the voluntary instrument “green public procurement” (GPP) was already identified as a driver for gypsum recycling by EU plasterboard manufacturers, particularly in countries such as Germany and Belgium (GtoG project, 2013b), which is in line with the findings of Garbarino and Blengini (2013) on the main drivers that can enhance C&D waste recycling. In our study, “Green Public Procurement criteria” (CF12) was rated as important or extremely important by 79% of respondents (see Fig. 3.1). This validates the previous findings and agrees with the last developments on GPP criteria for gypsum boards as described below. In 2010, the gypsum industry developed with the European Commission the green public procurement criteria for wall panels (GtoG project, 2013b). The document includes a proposal for core and comprehensive criteria, such the “Encourage the purchase of gypsum wall panels using synthetic gypsum and recycling gypsum” (European Commission, 2010). Moreover, the Commission has recently announced future actions on GPP as part of the EU Action plan for the circular economy (European Commission, 2015).

3.3.2. *Economic, social and environmental domains*

Fig. 3.2 shows complementary graphical representations of the critical economic, social and environmental aspects, both on the percentage of respondents selecting a particular rate (5=extremely important, 4=important, 3=neutral, 2=unimportant, 1=negligible) and the average mean rank obtained for GR and NGR countries.

Fig. 3.2. Additional analysis on the factors part of the economic, social and environmental domains. Breakdown into respondents' rate (left) and group of countries (right). GR countries: BE, UK, FR, NL, DK. NGR countries: AU, DE, GR, SP, PT.

3.3.3. Economic domain

Three factors were identified as crucial by respondents: price of the recycled gypsum (CF3), recycler's gate fee (CF6), and landfill operation cost (CF7) (see Table 3.2). These economic factors, along with those falling into the category Policy-Economic (see "Economic and general policy instruments" section), influence the competitiveness of gypsum recycling compared to landfill disposal.

The "Price of the recycled gypsum" (CF3) was rated as important or extremely important by 88% of respondents. In average, stakeholders in NGR countries valued CF3 slightly higher than those in GR countries (see Fig. 3.2). As Oyedele et al. (2014) found, one of the impediments to the use of recycled materials in the construction sector is that "Materials selection and specification are influenced by cost rather than environmental benefits". Indeed, the integration between economic, social and environmental aspects is needed (Yuan et al., 2011). At present, recycled gypsum is available at a lower price than natural gypsum, and EU plasterboard manufacturers identified "cost savings" and one of the seven drivers for using recycled gypsum. The average sales price calculated in the GtoG project equals to zero euro/tonne (GtoG project, 2013b).

"Recycler's gate fee" (CF6) is typically paid to the operator of the recycling facility by owners of the waste. This charge may vary with the sales price of the recycled gypsum (CF3) and the transportation distances for recycled gypsum (GtoG project, 2013b). CF6 was rated as important or extremely important by 89% of respondents, being the mean value of both groups of countries very similar (see Fig. 3.2). According to gypsum recyclers within the GtoG project, the average recycler's gate fee is 50 euro/tonne (GtoG project, 2013b).

When economic issues take precedence over any other factor, "Recycler's gate fee" (CF6) is likely to be compared to the standard cost of landfilling (composed of CF7 and CF2 "Landfill tax", being CF2 previously discussed in "Economic and general policy instruments" section). The "Landfill operation cost" (CF7) may determine the final decision of construction agents, as the operating cost increase between 30% and 230% when monocell landfills operate (GtoG project, 2013b). The requirement of

landfilling gypsum waste in monocell landfills was introduced in the European Union in 2003 (The Council of the European Union, 2003). However, monocell landfills are observed in a limited number of countries, such as Belgium, the UK and France (GtoG project, 2013b). This may be the reason why GR countries value such measure above NGR countries (probably because of the inexistence of monocell landfills in such regions). A report from Eurogypsum foresees a critical change on the economics of gypsum recycling due to the shortage of monocell landfills and higher landfill costs (Eurogypsum, 2007).

3.3.4. *Social and environmental domain*

The “Availability of natural/FGD gypsum” (CF4) can be considered an environmental factor that affect the uptake of recycled gypsum. 79% of respondents identified this factor as important or extremely important for closed-loop gypsum recycling. Until the 1980s, most of the gypsum feedstock was natural. Then, FGD gypsum started to be produced in Western Europe, and countries such as Belgium, the Netherlands and Nordic Countries, import it. Interestingly, such countries also lead the use of recycled gypsum (GtoG project, 2013b). The high availability of primary raw materials, along with their low prices, have been identified as a barrier towards the 70% recovery target by 2020 (European Commission, 2011).

With respect to social issues with environmental implications, three factors were selected as critical: “Awareness of the impacts of gypsum recycling and gypsum landfilling” (CF5), “Objectives and targets on waste management” (CF8), and “Collaboration between stakeholders” (CF11). These three social factors were the least valued in the economic-social-environmental domain by NGR countries (see Fig. 3.2).

“Awareness of the impacts of gypsum recycling and gypsum landfilling” (CF5) demonstrated a highly significant difference between the views of GR and NGR respondents (see Table 3.2, Mann-Whitney U test, $p < 0.001$). GR respondents rated CF5 as critical, whereas NGR respondents rated it as one of the least valued CFs (see Table 3.2). Overall, 35% of respondents considered that such awareness is extremely important for a circular economy around gypsum. Our finding compares well with those reported by previous authors. For instance, in the study conducted by Lu & Yuan (2010) on factors for C&D waste management in China, the awareness ranked third ($M=3.53$; $SD=0.45$), which is a similar value to that resulting in our European NGR contexts. In a more recent study, Yuan (2013a) identified “Improving Major Stakeholders’ Awareness about Resource Savings and Environmental Protection” as a critical management measure, ranking fifth for the case of China ($M=4.188$; $SD=0.67$).

Two factors “Collaboration between stakeholders” (CF11) and the setting of “Objectives and targets on waste management” (CF8), indicate stakeholder’s engagement on a particular action, and are commonly interrelated. The signature of voluntary agreements standards and schemes; mechanisms that includes targets and timeline related to gypsum recycling, typically cover both CFs. Mann-Whitney U test showed a significant different on how GR and NGR view CF11 (see Table 3.2, $p < 0.05$). This is in line with the fact that NGR countries are unfamiliar with value chain voluntary agreements on gypsum recycling, which have been only found in three European countries: France, the Netherlands and the

UK. In 2008, a voluntary agreement “La Charte sur la Gestion des déchets” (Les Industries du Plâtre, 2008), was signed by the French gypsum manufacturers through their industrial association “Les Industries du Plâtre”, with the intention of promoting the proper management of post-consumer gypsum waste coming from C&D waste generated. In the Netherlands a covenant to close the gypsum cycle in the building sector has been drawn up, with the objective of doubling the recycling rates for gypsum from C&D waste (from 20% in 2008 to 40% in 2010) and converting this country in the European leader in the field of gypsum recycling in 2015, “Convenant voor sluiten van kringloop van gips in bouwsector” (De Minister van Volkshuisvesting et al, 2008). Several agreements related to the plasterboard sector can be found in the UK: the Ashdown Agreement, the Contractors Agreement on Reducing Waste, the Demolition Waste Action Plan, and the End of life plasterboard waste agreement (see (Department for Environment Food and Rural Affairs - defra and the Plasterboard Sustainability Partnership - psp, 2013) for further details). For instance, the Ashdown Agreement in the UK (WRAP, 2010) covers four targets including the engagement with all stakeholders and the reduction of the waste sent to landfill.

3.4. Conclusions

This investigation set out to determine critical factors (CFs) for gypsum recycling in the European Union. Factors were first identified based on a review of the literature and findings from the Life+ GtoG project. These factors were further examined by conducting a questionnaire that targeted the main agents of the value chain. Data analysis revealed a set of CFs that were categorized into four domains: policy, economic, social, and environmental aspects. More than a half of the CFs relate to policy instruments, being five of them regulatory instruments. This indicates the relevant role of governments to strengthen waste legislation, regulatory frameworks and the enforceability of such instruments in line with the circular economy principles.

Particularly, the following regulatory aspects are identified as critical: “Landfill ban” (CF1), “Regulatory framework favouring the use of recycled materials” (CF9), “Regulatory framework favouring building deconstruction” (CF10), “Legal alternative destinations that do not favour the options that are higher in the waste hierarchy” (CF13), and “Regulatory framework favouring site waste management plan (CF15)”. These have to be accompanied by economic incentives, control measures and other policy instruments, including “Landfill tax” (CF2), “Other levies and fines” (CF14), and “Green Public Procurement” (CF12). Such economic instruments along with other economic factors (i.e. “Price of the recycled gypsum” (CF3), “Recycler’s gate fee” (CF6) and “Landfill operation cost” (CF7)), determine the competitiveness of gypsum recycling versus disposal, and become vital to create and develop markets for recycled materials. In addition, the critical social and environmental factors involve “Availability of natural and/or FGD gypsum” (CF4), “Awareness of the impacts of gypsum recycling and gypsum landfilling” (CF5), “Objectives and targets on waste management” (CF8), and “Collaboration between stakeholders” (CF11), maintaining the triple bottom line perspective of economic, social and environmental sustainability. It should be noted that respondents from gypsum recycling and non-gypsum recycling countries hold different views on the critical factors. Those performing their activity in non-gypsum recycling countries generally rated the importance of the factors lower than those working in gypsum recycling countries, except those factors related to economic

aspects (e.g. “Other levies and fines”, “Price of the recycled gypsum”). These findings may imply that stakeholders in non-gypsum recycling countries mostly rely on economic aspects to enhance the recovery of gypsum waste. For its part, responses from gypsum recycling countries show a higher balance between economic, social, and environmental aspects.

Although the CFs here identified are applicable to any European context, the results are subject to certain limitations. For instance, some factors are interrelated with each other and certain combinations of factors may result in more general factors (e.g. investment climate). Consequently, additional quantitative assessment could be investigated in order to set out the relationship between CFs. Notwithstanding this, the 15 CFs can assist decision-makers and stakeholders as follows. On the one hand, decision-makers count with a framework to improve the functioning of the gypsum value chain. On the other hand, stakeholders can better comprehend what factors influence their activity and therefore the factors that should be taken into consideration in order to improve a given situation. Moreover, these CFs are considered to be valuable references for other waste streams and specific national contexts.

References

- Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry : Understanding the impediments and requisites for improvements. *Resources, Conservation & Recycling*, 102, 101–112. <http://doi.org/10.1016/j.resconrec.2015.06.001>
- Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources, Conservation and Recycling*, 105, 167–176. <http://doi.org/10.1016/j.resconrec.2015.10.018>
- Ali, H. A. E. M., Al-Sulaihi, I. A., & Al-Gahtani, K. S. (2013). Indicators for measuring performance of building construction companies in Kingdom of Saudi Arabia. *Journal of King Saud University - Engineering Sciences*, 25(2), 125–134. <http://doi.org/10.1016/j.jksues.2012.03.002>
- Antink, R., Garrigan, C., Bonetti, M., & Westaway, R. (2014). Greening the Building Supply Chain. UNEP Sustainable Buildings and Climate Initiative. United Nations Environment Programme. Job Number: DTI/1753/PA. Retrieved 17 January 2016, from http://www.unep.org/sbci/pdfs/greening_the_supply_chain_report.pdf
- Barbudo, A., Galvín, A. P., Agrela, F., Ayuso, J., & Jiménez, J. R. (2012). Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes. *Waste Management*, 32(6), 1229–35. <http://doi.org/10.1016/j.wasman.2012.02.005>
- Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2009). Attitude and behavioral factors in waste management in the construction industry of Malaysia. *Resources, Conservation and Recycling*, 53(6), 321–328. <http://doi.org/10.1016/j.resconrec.2009.01.005>
- Carmines, E. G., & Zeller, R. A. (1979). Reliability and validity assessment. *Quantitative Applications in the Social Sciences*. <http://doi.org/10.1037/018269>
- Cheng, J. C. P., & Ma, L. Y. H. (2013). A BIM-based system for demolition and renovation waste estimation and planning. *Waste Management*, 33(6), 1539–1551. <http://doi.org/10.1016/j.wasman.2013.01.001>
- CIB International Council for Research and Innovation in Building and Construction. (2014). Barriers for Deconstruction and Reuse / Recycling of Construction Materials. (U. S. A. Shiro Nakajima, Building Research Institute, Japan Mark Russell, University of New Mexico, Ed.). CIB Publication 397.

- Coelho, A., & de Brito, J. (2011). Economic analysis of conventional versus selective demolition—A case study. *Resources, Conservation and Recycling*, 55(3), 382–392. <http://doi.org/10.1016/j.resconrec.2010.11.003>
- Couto, J., & Couto, A. (2010). Analysis of barriers and the potential for exploration of deconstruction techniques in Portuguese construction sites. *Sustainability*, 2(2), 428–442. <http://doi.org/10.3390/su2020428>
- Dantata, N., Touran, A., & Wang, J. (2005). An analysis of cost and duration for deconstruction and demolition of residential buildings in Massachusetts. *Resources, Conservation and Recycling*, 44(1), 1–15. <http://doi.org/10.1016/j.resconrec.2004.09.001>
- De Minister van Volkshuisvesting et al. (2008). Covenant voor publiek-private samenwerking voor het sluiten van de kringloop van gips in de bouwsector. K&K 2008052604.
- Delgado, L., Sofia-Catarino, A., Eder, P., Litten, D., Luo, Z., & Villanueva, A. (2009). End of waste criteria. Final Report.
- Deloitte. (2015). Construction and Demolition Waste management in United Kingdom. V3 - December 2015. Retrieved 4 May 2016, from http://ec.europa.eu/environment/waste/studies/deliverables/CDW_UK_Factsheet_Final.pdf
- Department for Environment Food and Rural Affairs - defra. (2013). Defra Public Consultations. Proposed repeal of construction Site Waste Management Plan Regulations (2008). Summary of responses and Government response.
- Department for Environment Food and Rural Affairs - defra and the Plasterboard Sustainability Partnership - psp. (2013). Plasterboard Sustainability Action Plan. 2nd Annual Report 2013.
- Duran, X., Lenihan, H., & O'Regan, B. (2006). A model for assessing the economic viability of construction and demolition waste recycling—the case of Ireland. *Resources, Conservation and Recycling*, 46(3), 302–320. <http://doi.org/10.1016/j.resconrec.2005.08.003>
- Emma Watkins, Dominic Hogg, Mitsios, A., Mudgal, S., Neubauer, A., Reisinger, H., ... Acoleyen, M. Van. (2012). Use of Economic Instruments and Waste Management Performances - Final Report. Retrieved from http://ec.europa.eu/environment/waste/pdf/final_report_10042012.pdf
- Environment Agency. (2012). An investigation into the disposal and recovery of gypsum waste. Report - HOOP000153/R.
- Eurogypsum. (2007). Eurogypsum Waste Policy: Building Value For Society.
- European Commission. (2014). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on Resource Efficiency Opportunities in the Building Sector, COM(2014) 445 final. Retrieved from <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0445&from=EN>
- European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy (2015). Retrieved from http://ec.europa.eu/environment/circular-economy/index_en.htm
- European Commission (DG ENV). (2010). Green Public Procurement Wall Panels Technical Background Report.
- European Commission (DG ENV). (2011). Service Contract on Management of Construction and Demolition Waste - SR1. Final Report Task 2. A project under the Framework contract ENV.G.4/FRA/2008/0112. Retrieved 17 January 2016, from http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf
- European Parliament and the Council of the European Union. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Retrieved 12 April 2015, from <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:en:PDF>
- Field, J. M., & Sroufe, R. P. (2007). The use of recycled materials in manufacturing: implications for supply chain management and operations strategy. *International Journal of Production Research*, 45(18–19), 4439–4463. <http://doi.org/10.1080/00207540701440287>

- Finnveden, G., Ekvall, T., Arushanyan, Y., Bisaillon, M., Henriksson, G., Östling, U. G., ... Guath, M. (2013). Policy instruments towards a sustainable waste management. *Sustainability*, 5(3), 882–895. <http://doi.org/10.3390/su5030882>
- Fischer, C., Lehner, M., & Mckinnon, D. L. (2012). Overview of the use of landfill taxes in Europe.
- Garbarino, E., & Blengini, G. A. (2013). The economics of construction and demolition waste management facilities. *Handbook of Recycled Concrete and Demolition Waste*. Woodhead Publishing Limited. <http://doi.org/10.1533/9780857096906.2.304>
- GtoG project. (2013a). Life+ Gypsum to Gypsum (GtoG) project ‘From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry’ LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4191
- GtoG project. (2013b). DA1: Inventory of current practices LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from <http://gypsumtogypsum.org/documents/deliverable-a1-report-on-current-practices.pdf>
- GtoG project. (2015a). DC2: Protocol of action B2.2: Quality criteria for recycled gypsum, technical and toxicological parameters LIFE11 ENV/BE/001039. Retrieved 13 November 2015, from <http://gypsumtogypsum.org/documents/quality-criteria-for-recycled-gypsum-technical-and-toxicological-parameters.pdf>
- GtoG project. (2015b). DA2: Inventory of best practices LIFE11 ENV/BE/001039. Retrieved 17 July 2016, from <http://gypsumtogypsum.org/documents/da2-inventory-of-best-practices.pdf>
- Harpe, S. E. (2015). How to analyze Likert and other rating scale data. *Currents in Pharmacy Teaching and Learning*, 7(6), 836–850. <http://doi.org/10.1016/j.cptl.2015.08.001>
- Jiménez-Rivero, A., & García-Navarro, J. (2016). Indicators to Measure the Management Performance of End-of-Life Gypsum: From Deconstruction to Production of Recycled Gypsum. *Waste and Biomass Valorization*, 1–15. article. <http://doi.org/10.1007/s12649-016-9561-x>
- Jiménez Rivero, A., De Guzmán Báez, A., & García Navarro, J. (2015). Gypsum Waste: Differences across Ten European Countries. *International Journal of Sustainability Policy and Practice*, 11(4), 1–9.
- Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources, Conservation and Recycling*, 108, 171–181. <http://doi.org/10.1016/j.resconrec.2016.01.014>
- Klang, A., Vikman, P.-Å., & Brattebø, H. (2003). Sustainable management of demolition waste—an integrated model for the evaluation of environmental, economic and social aspects. *Resources, Conservation and Recycling*, 38(4), 317–334. [http://doi.org/10.1016/S0921-3449\(02\)00167-2](http://doi.org/10.1016/S0921-3449(02)00167-2)
- Kulatunga, U., Amaratunga, D., Haigh, R., & Rameezdeen, R. (2006). Attitudes and perceptions of construction workforce on construction waste in Sri Lanka. *Management of Environmental Quality: An International Journal*, 17(1), 57–72. <http://doi.org/10.1108/14777830610639440>
- Les Industries du Plâtre. (2008). Charte de Gestion des Déchets de Plâtre.
- Li, M., & Yang, J. (2014). Critical factors for waste management in office building retrofit projects in Australia. *Resources, Conservation and Recycling*, 93, 85–98. <http://doi.org/http://dx.doi.org/10.1016/j.resconrec.2014.10.007>
- Lieder, M., & Rashid, A. (2015). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, 115, 36–51. <http://doi.org/10.1016/j.jclepro.2015.12.042>
- Lönngren, H.-M., Rosenkranz, C., & Kolbe, H. (2010). Aggregated construction supply chains: success factors in implementation of strategic partnerships. *Supply Chain Management: An International Journal*, 15(5), 404–411. <http://doi.org/10.1108/13598541011068297>
- Lu, W., Shen, L., & Yam, M. (2008). Critical success factors for competitiveness of contractors: A China study. *Journal of Construction Engineering and Management*, 134(December), 972–982. [http://doi.org/10.1061/\(ASCE\)0733-9364\(2008\)134:12\(972\)](http://doi.org/10.1061/(ASCE)0733-9364(2008)134:12(972))

- Lu, W., & Yuan, H. (2010). Exploring critical success factors for waste management in construction projects of China. *Resources, Conservation and Recycling*, 55(2), 201–208.
<http://doi.org/10.1016/j.resconrec.2010.09.010>
- Merriam-Webster. (2015). Merriam-Webster. In Merriam-Webster.
- Morris, J. R., Phillips, P. S., & Read, A. D. (1998). The UK Landfill Tax: An analysis of its contribution to sustainable waste management. *Resources, Conservation and Recycling*, 23(4), 259–270. [http://doi.org/10.1016/S0921-3449\(98\)00037-8](http://doi.org/10.1016/S0921-3449(98)00037-8)
- OECD. (2003). Environmentally Sustainable Buildings.
- Oyedele, L. O., Ajayi, S. O., & Kadiri, K. O. (2014). Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement. *Resources, Conservation and Recycling*, 93, 23–31.
<http://doi.org/10.1016/j.resconrec.2014.09.011>
- Pacheco-Torgal, F., Tam, V. W. Y., Labrincha, J. A., Ding, Y., & Brito, J. de. (2013). Conventional demolition versus deconstruction techniques in managing construction and demolition waste (CDW). *Handbook of recycled concrete and demolition waste*. Woodhead Publishing Limited.
<http://doi.org/http://dx.doi.org/10.1533/9780857096906.2.141>
- Poon, C. S., Yu, A. T. W., & Ng, L. H. (2001). On-site sorting of construction and demolition waste in Hong Kong. *Resources, Conservation and Recycling*, 32(2), 157–172.
[http://doi.org/10.1016/S0921-3449\(01\)00052-0](http://doi.org/10.1016/S0921-3449(01)00052-0)
- Rockart, J. F. (1979). Chief executives define their own data needs. *Harvard Business Review*, 57(2), 81–93.
- Rodríguez-Quijano, M., Jiménez-Rivero, A., de Guzmán-Báez, A., & García-Navarro, J. (2015). Gypsum plasterboard deconstruction to recycling economic study in Europe. In *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM (Vol. 1, pp. 665–674)*.
- Scharff, H. (2014). Landfill reduction experience in The Netherlands. *Waste Management*, 34(11), 2218–2224. <http://doi.org/10.1016/j.wasman.2014.05.019>
- Seror, N., Hareli, S., & Portnov, B. A. (2014). Evaluating the effect of vehicle impoundment policy on illegal construction and demolition waste dumping: Israel as a case study. *Waste Management (New York, N.Y.)*, 34(Seror, N(8), 1436–45. <http://doi.org/10.1016/j.wasman.2014.03.026>
- Tam, V. W. Y. (2008). On the effectiveness in implementing a waste-management-plan method in construction. *Waste Management*, 28(6), 1072–1080.
<http://doi.org/10.1016/j.wasman.2007.04.007>
- Tam, V. W. Y., & Tam, C. M. (2006). Evaluations of existing waste recycling methods: A Hong Kong study. *Building and Environment*, 41(12), 1649–1660.
<http://doi.org/10.1016/j.buildenv.2005.06.017>
- Teo, M. M. M., & Loosemore, M. (2001). A theory of waste behaviour in the construction industry. *Construction Management and Economics*, 19(7), 741–751.
<http://doi.org/10.1080/01446190110067037>
- The Council of the European Union. (2003). Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex to Directive 1999/31/EC (2003/33/EC). *Official Journal of the European Communities*, L 11/27-11/49.
- Villoria Saez, P., Del Río Merino, M., San-Antonio González, A., & Porras-Amores, C. (2013). Best practice measures assessment for construction and demolition waste management in building constructions. *Resources, Conservation and Recycling*, 75, 52–62.
<http://doi.org/10.1016/j.resconrec.2013.03.009>
- Wang, J., Yuan, H., Kang, X., & Lu, W. (2010). Critical success factors for on-site sorting of construction waste: A china study. *Resources, Conservation and Recycling*, 54(11), 931–936.
<http://doi.org/10.1016/j.resconrec.2010.01.012>
- WRAP. (2010). Annual review. Ashdown Agreement Annual Report to 31 March 2010.

- WRAP. (2012). Landfill Bans: Feasibility Research. The environmental, economic and practical impacts of landfill bans or restrictions: research to determine feasibility. Retrieved from [http://www.wrap.org.uk/sites/files/wrap/Landfill Bans Feasibility Research Final Report Updated.pdf](http://www.wrap.org.uk/sites/files/wrap/Landfill%20Bans%20Feasibility%20Research%20Final%20Report%20Updated.pdf)
- WRAP. (2014). Achieving good practice Waste Minimisation and Management. Practical Solutions for Sustainable Construction, 43. Retrieved from http://www2.wrap.org.uk/downloads/achieving_good_practice_waste_minimisation_and_management.3494db01.5139.pdf
- WRAP, & Environment Agency. (2013). Quality Protocol. Gypsum. End of waste criteria for the production and use of recycled gypsum from waste plasterboard.
- Ya'cob, A. S., Zawawi, W. N. A. A., Isa, M. H., & Othman, I. (2013). Factors that affect sustainable construction waste management efforts at site. In WIT Transactions on Ecology and the Environment. 8th International Conference on Urban Regeneration and Sustainability, SC 2013; Putrajaya; Malaysia; 3 December 2013 through 5 December 2013 (Vol. 179, pp. 1169–1176). <http://doi.org/10.2495/SC130992>
- Yuan, F., Shen, L., & Li, Q. (2011). Emergy analysis of the recycling options for construction and demolition waste. Waste Management, 31(12), 2503–11. <http://doi.org/10.1016/j.wasman.2011.07.001>
- Yuan, H. (2013). Critical Management Measures Contributing to Construction Waste Management: Evidence From Construction Projects in China. Project Management Journal, 44(4), 101–112. <http://doi.org/10.1002/pmj.21349>

PART III: MICRO-LEVEL

BACKGROUND INFORMATION: CASE STUDIES

At the micro-level, this thesis focuses on specific deconstruction-recycling value chains. In particular, Chapter 4 and Chapter 5 are mainly based on data collected from the GtoG case studies, also referred as GtoG pilot projects. These case studies covered deconstruction, recycling and manufacturing processes in four countries: Belgium, France, Germany and the United Kingdom. Chapter 6 for its part focuses on best practices for an improved deconstruction-recycling value chain. Further information on the case studies can be found in Chapter 5, Section 5.4. Monitoring of European pilot projects.

4 PHYSICAL AND MECHANICAL CHARACTERIZATION

CHAPTER OVERVIEW

The quality of secondary materials is imperative to promote a circular economy. In order to improve the way in which gypsum waste (GW) is treated, European guidelines on recycled gypsum (RG) quality criteria have been outlined in the framework of the Life+ Gypsum to Gypsum (GtoG) project. Such guidelines, along with the European Standard on gypsum plasterboard EN 520, provided the basis for this study. During the GtoG project, gypsum recycling and plasterboard manufacturing processes were monitored by testing the gypsum feedstock and the resulting plasterboard. The aim of the present chapter is to discuss the results obtained on relevant parameters that characterize gypsum as a secondary raw material, as well as the resulting product.

Under review in “Materiales de Construcción”

Main research questions addressed and relation to other chapters

	Research question (and related specific objective in parentheses)	Brief answer and → Relation with other chapters
<div>Chapter 1. Gypsum waste generation and management</div> <div>Chapter 2. Life cycle energy and material flows</div> <div>Chapter 3. Factors influencing post-consumer gypsum recycling</div> <div>PART II: MACRO-LEVEL</div>	How does recycled gypsum (RG) compare with business-as-usual gypsum feedstock? (O4)	Only 56% of the RG gypsum feedstock showed compliance with the limit values of the “GtoG guidelines” on RG quality criteria. However, the limit values (technical parameters) have to be adapted to the specifics of each plant (for instance all RG was considered appropriate during the GtoG pilot projects, and only one manufacturer reported 20% of not usable material) ^a . →
<div>Chapter 4. Physical and mechanical characterization</div> <div>Chapter 5. End-of-life case studies analysis</div> <div>Chapter 6. Best practices in the end-of-life stage</div> <div>PART III. MICRO-LEVEL</div>		As practices during the deconstruction and recycling processes have a great influence on the final quality of the RG, Chapter 5 analyses the performance of the GtoG case studies. Moreover, Chapter 6 proposes fundamental practices to produce quality recycled gypsum from end-of-life gypsum.

^a GtoG project. (2015). DC1. Report on best practice indicators for deconstruction, recycling and reincorporation LIFE11 ENV/BE/001039.

4.1. Introduction

Gypsum products mainly consist of calcium sulphate dehydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), from three distinct sources: nature (mines or quarries), industrial processes and urban mining. It is feasible to recycle gypsum sourced from urban mining (known as end-of-life (EoL) gypsum or post-consumer gypsum waste). In order to be recyclable, gypsum-based systems typically require deconstruction and separate collection of gypsum waste (further details on the ideal conditions to produce quality RG from urban mining can be found in (Jiménez-Rivero & García-Navarro, 2016)). However, the use of post-consumer RG is still very low in the European Union. For example, the weight percentage of post-consumer RG in a reference plasterboard in the year 2013 in the European Union was estimated to be 1% (Jiménez Rivero et al., 2016). In such reference plasterboard, three types of gypsum are dominant. Natural gypsum (i.e. from mines or quarries, 63%), synthetic gypsum (i.e. from industrial processes, by-product mainly from flue gas desulfurization systems, 27%) and pre-consumer RG (from industrial processes, waste generated during the manufacturing process, commonly known as pre-consumer waste or industrial waste, 4%). The remaining 5% correspond to lining paper and additives. Worth noting is that, in the European Union, a market for post-consumer RG has only emerged in Benelux, Scandinavia, France, the Netherlands and the UK (Jiménez Rivero et al., 2015).

Landfilling becomes the common destination of EoL gypsum in countries where a market for post-consumer RG has not yet emerged. Gypsum landfilling typically contributes to primary resource depletion, hydrogen sulphide and methane emissions from landfills (Jiménez Rivero et al., 2016). Around 1.9 million tonnes of EoL plasterboard were estimated to be generated in 2013 in the European Union, of which only 12.7% were recovered. Different measures currently aim to mitigate such emissions, such as gypsum landfilling in specific monocells (The Council of the European Union, 2003) or the examination of alternative landfill cover soils (Plaza, Xu, Townsend, Bitton, & Booth, 2007). But recycling, apart from avoiding the above mentioned harmful effects, is a mechanism to achieve resource efficiency and contribute to sustainable development (Ding, 2008).

The resulting RG can be used to manufacture new gypsum products, as a set retarder in Portland cement (Chandara et al., 2009; Suárez, Roca, & Gasso, 2016) and to improve and treat soil (Kuttah & Sato, 2015). Gypsum is also a source of calcium and nutrient sulphur in agriculture (background information on the use of recovered soil fines from construction and demolition waste can be found in the study conducted by Jang and Townsend (2001), in which the leaching of sulphate from these fines due to the presence of gypsum plasterboard is examined). The present study explores the use of RG by the gypsum industry, which implies that the material loop is closed and enables the future re-use or recycling of the same gypsum products.

In order to be usable, RG should comply with the quality criteria threshold agreed between the final costumer and the recycler. Little was published about the diverse RG quality criteria before the beginning of the European Life+ Gypsum to Gypsum project “From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry” (GtoG project, 2013a). Knowledge on such existing quality criteria (see (Jiménez Rivero et al., 2015) for extended

information) can guide new costumers of RG (i.e. manufacturers aiming to reincorporate RG in their process) towards preparing the most suitable agreements according to the nature of the manufacturing process (e.g. use of natural or synthetic feedstock, equipment). Moreover, the GtoG project has produced a set of European voluntary guidelines on the RG quality criteria for the gypsum industry, as a result of three years of collaborative works between agents' part of the value chain. The works included pilot projects (deconstruction, recycling and manufacturing processes) in distinct European locations (France, the UK, Germany, Belgium and the Netherlands). Producers, recyclers and laboratory Loemco (Official Laboratory for Testing Materials of Construction, third party laboratory, partner of the GtoG project) discussed the test results and agreed on initial guidelines (GtoG project, 2015a). These are the first harmonised guidelines at EU level covering technical and toxicological parameters (hereinafter GtoG guidelines on RG quality criteria).

The present study focuses on test results from five European pilot projects, which included 21 gypsum feedstock samples and 13 plasterboard samples. The aim is to analyse relevant parameters that characterize gypsum as a raw material (business-as-usual gypsum feedstock and RG feedstock) and gypsum products (business-as-usual plasterboard and plasterboard with up to 30% reincorporation of RG). The paper discusses the quality of the gypsum feedstock against the GtoG guidelines on RG quality criteria (see "Gypsum as feedstock: business-as-usual versus recycled gypsum feedstock" section) as well as the properties of the final products against the relevant standard (CEN, 2009), as detailed in "Plasterboard: business-as-usual versus plasterboard with increased RG content" section. The samples were collected by Loemco during the GtoG project, between February 2014 and January 2015. Most of the tests were carried out by this laboratory, except those related to radioactivity, mercury testing and total organic carbon, which were conducted by Laboratory for Gamma-ray Spectrometry in Belgium (SCK- CEN), Institut Frenesius in Germany (SGS) and Instituto Técnico de Materiales y Construcciones in Spain (Intemac), respectively.

4.2. Materials and methods

4.2.1. Gypsum feedstock: recycled gypsum quality criteria

Sources of gypsum for plasterboard production include gypsum mining, flue gas desulfurization (FGD) gypsum, and recycled products. Other required plasterboard inputs include paper and additives.

The experimental methods for the assessment of the RG quality criteria parameters are based on four European documents as follows. The Instruction Sheet VGB-M 701 (VGB, 2008) for the case of free moisture, purity, salts and pH; the European Standard EN 933-1 for the particle size results (maximum size measured in Table 4.1 and particles below 4 mm in Fig. 4.1); EN 13137 for assessing the total organic carbon (TOC) and EN ISO 11885 for analysing the toxicological parameters. Additionally, the radioactivity index was calculated according to the RP 112 document (EC) and the asbestos content was analysed according to the Rietveld method (GtoG project, 2015a).

The limit values of the technical parameters (see column "GtoG project guidelines" in Table 4.1) are based on previous criteria developed by the quality protocol in the UK (WRAP & Environment Agency, 2013) and BV Gips in Germany (Bundesverband der Gipsindustrie e.V., 2013), being the later used as

a benchmark. The guidelines for the toxicological parameters (see column “GtoG project guidelines” in Table 4.3) are also based on the criteria developed by BV Gips in Germany (Bundesverband der Gipsindustrie e.V., 2013), which in turn is based on the study conducted by Beckert on natural and FGD gypsum (Beckert, 1990).

The raw materials object of study (natural, FGD and RG) were collected from the GtoG pilot projects (N=21). These included business-as-usual and RG feedstock as detailed below.

- Business-as-usual gypsum feedstock (GY_{BAU}) for plasterboard manufacturing (N=8). Samples were labelled as GY-F/M/R-No. Three samples come from plants using FGD gypsum (GY-F-01, GY-F-02 and GY-F-03). Four samples come from plants using mined gypsum (GY-M-01, GY-M-02, GY-M-03 and GY-M-04). One sample corresponded to pre-consumer RG (GY-R-01).
- RG feedstock (GY_{RG}) for plasterboard manufacturing (N=13), including pre-consumer (from plasterboard production) and post-consumer RG samples (gypsum-based systems were dismantled from renovation works, segregated on-site and transported to the recycler. Further details on the pilot projects can be found in Chapter 5, Section 5.6. “Monitoring of European Pilot Projects”). Samples were labelled as RG-No.

4.2.2. *Plasterboard: physical and mechanical properties*

Plasterboard samples were tested by Loemco during the GtoG pilot projects according to the European standard EN 520:2005+A1:2010 (CEN, 2009). In this study we examined the density (kg/m³), flexural strength (expressed as flexural breaking load) both transverse and longitudinal direction (N), surface water absorption (g/m³) and surface hardness (mm) results.

Plasterboard samples were type A, considered as the standard plasterboard (CEN, 2009), with nominal board thickness of 12.5 mm. Further details on the samples are detailed below.

- Business-as-usual plasterboard (PB_{BAU}) (N=6). In these five plants, common reincorporation rates of RG ranges from 5% to 15% by weight.
- Plasterboard with increased RG content (PB_{RG}) (N=7). During the GtoG production trials the new composition included between 17 and 28% of RG content (i.e. the plasterboard sample with lower RG content achieved 17% by weight).

4.3. Results and discussion

4.3.1. *Gypsum as feedstock: business-as-usual versus recycled gypsum feedstock*

Table 4.1 and Fig. 4.1 show information on the average results obtained for the technical parameters. These parameters, along with the toxicological ones (detailed in Table 4.3) are part of the quality criteria for the use of RG into new gypsum products.

Table 4.1. Technical parameters analysis

Parameter	Unit	Reference standard	GtoG project guidelines ^a	GY _{BAU}				GY _{RG}			
				M	SD	Min	Max	M	SD	Min	Max
Maximum size	mm	EN 933-1	15.00	7.38	9.89	0.10	20.00	8.00	4.00	2.00	14.00
Free moisture	% w/w	VGB-M 701	<10	3.02	3.01	0.05	6.85	6.91	5.05	0.27	17.14
Purity	% w/w	VGB-M 701	>80	91.78	2.57	89.01	96.41	87.41	3.36	79.83	90.64
Total organic carbon	% w/w	EN 13137	<1.5	0.17	0.28	0.01	0.83	0.85	0.72	0.19	3.13
Magnesium salts	% w/w	VGB-M 701	<0.1	0.01	0.00	0.00	0.01	0.02	0.01	0.01	0.04
Sodium salts	% w/w	VGB-M 701	<0.06	0.01	0.01	0.00	0.02	0.02	0.01	0.02	0.07
Potassium salts	% w/w	VGB-M 701	<0.05	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.04
Soluble chloride	% w/w	VGB-M 701	<0.02	0.00	0.00	0.00	0.01	0.02	0.03	0.01	0.12
pH	-	VGB-M 701	6-9	7.54	0.65	6.50	8.51	8.13	0.47	7.53	8.91

^a In accordance with (GtoG project, 2015a). Total organic carbon (TOC), magnesium salts (MgO), sodium salts (Na₂O), potassium salts (K₂O), soluble chloride (Cl). M: mean value; SD: standard deviation; Min: minimum; Max: maximum. Maximum size measured could not be assessed for the samples GY-M-02 and GY-M-04.

Fig. 4.1. Detailed values per sample on the particle size results (in terms of rate of particles below 4 mm), free moisture, purity and total organic carbon. GY_{BAU} includes samples labelled as GY-F/M/R-No. M refer to natural or mined gypsum. F: FGD gypsum. R: RG. A sample labelled GY-F-01 comes from standard feedstock, mainly composed of FGD gypsum. GY_{RG} includes samples labelled as RG-No. Particles below 4 mm could not be measured for the samples GY-M-02 and GY-M-04.

— Particle size

The particle size was analysed in terms of the maximum size measured (see Table 4.1) and the particles below 4 mm (see Fig. 4.1). In average, GY_{BAU} and GY_{RG} had similar maximum size. However, the

deviation was higher for the case of GY_{BAU} (7.38 ± 9.89) compared to GY_{RG} (8.00 ± 4.00). Moreover, the minimum size varied greatly between samples (0.10 mm in the GY_{BAU} , compared to 2.00 mm in GY_{RG}). This is mainly due to plant specifics. For example, plants operating with FGD feedstock (GY-F-01, GY-F-02, GY-F-03), showed a maximum particle size of 0.1 mm, while plants using mined feedstock presented a maximum value of 20 mm. The requirements on particle size will therefore vary according to the needs of each plant. In this line, plants that use natural gypsum typically accept higher particle sizes while FGD plants have more strict requirements (GtoG project, 2015b).

Variations in the particle size distribution of feedstock may affect the calcination rate (i.e. higher times for coarser compared to finer particle sizes) and thereby the calcination efficiency. Thus, the particle size of RG should be in line with the conventional feedstock used by the manufacturer.

— Free moisture

The average free moisture obtained for GY_{BAU} (3.02 ± 3.01) compares well with data from Venta (1997), in which values between 1 and 3% free moisture content in natural gypsum are reported. The higher standard deviation is mainly due to GY_{BAU} samples from plants using mainly FGD as gypsum feedstock (e.g. GY-F-02 and GY-F-03, 6.64%w/w and 6.85%w/w free moisture content, respectively). This parameter was above the threshold (10 %w/w) in three of the 13 post-consumer RG samples object of study (RG-08, RG-09, RG-10, see Fig. 4.1), being the maximum value measured 17.14%w/w. Therefore, special attention should be paid to free moisture in order to comply with the RG quality criteria. This moisture in post-consumer RG can be limited with the use of covered skips for EoL gypsum from deconstruction to recycling, the duration and conditions of storage. Free moisture can be also reduced by mixing wet RG loads with drier ones (GtoG project, 2013b).

Reincorporation of RG with high free moisture content may pose a technical problem since the material would need additional drying operations. Such extra processes would require higher primary energy and costs. As a consequence, the Eurogypsum Recycling Working Group recommends to limit free moisture of RG to 5% (GtoG project, 2015a, 2015b).

— Purity

This parameter refers to the content of calcium sulphate dehydrate ($CaSO_4 \cdot 2H_2O$) in the material. As with the particle size, the purity of gypsum products varies between manufacturing plants. This is especially evident between gypsum products manufactured in plants using FGD gypsum (i.e. high purity, above 95% according to (WRAP and Environmental Resources Management Ltd (ERM), 2008)) compared to plants using natural gypsum (i.e. purity commonly ranges from 80% to 96% according to Henkels & Gaynor (1996); values in line with 91.28% purity measured by Chandara et al. (2009)). This variability will hence affect the purity of the EoL gypsum from the building stock. In this study, purity of GY_{BAU} was 4.37 % w/w higher compared to GY_{RG} . GtoG guidelines on RG quality criteria establish minimum 80% purity, and the Eurogypsum Recycling Working Group recommends a value of at least 85% (GtoG project, 2015a). In any case, these guidelines should be adapted to each particular context. For example, the Italian gypsum association demands purity higher than 75% by weight (Jiménez Rivero et al., 2015). By contrast, the UK document PAS 109 (WRAP & BSI, 2013) and BV Gips require values

above 85% w/w (Bundesverband der Gipsindustrie e.V., 2013). One sample (RG-04) did not comply (79.83% w/w purity) with the agreed GtoG guidelines (see Fig. 4.1). Such value could be suitable for cement production, which commonly require lower purities, probably because of the content variation in the process (Roskill, 2014).

Purity affects the primary energy use of the calcination stage during the manufacturing process, due to the content of chemically bound water (i.e. higher purity requires higher energy demand) (GtoG project, 2015b). On the other hand, the higher the purity, the lower the weight of the gypsum product and the effects of potential impurities, which makes higher purity a desired parameter (Henkels & Gaynor, 1996).

— Total organic carbon (TOC)

The value of TOC varies with the content of residual paper in the RG. This paper waste comes from the lining paper in plasterboard. Although the existing technology for processing EoL gypsum is designed to separate the paper from the gypsum core, traces of paper waste may remain in the recycled material. Such traces should be limited in order to warrant confidence on RG. In this study, one sample exceeded the TOC threshold in the GtoG guidelines on RG quality criteria (RG-01, TOC=3.13), which was attributed to the nature of this sample (RG-01 corresponded to only pre-consumer RG). Such high TOC values are likely to be found in pre-consumer RG. RG that comes from industrial waste is often recycled by the manufacturer, by using equipment that may not separate the lining paper from the gypsum core (GtoG project, 2013b).

High TOC values affect the fluidity of the slurry and increases the excess of water demand. The residual paper should therefore be kept at the minimum possible level. The Eurogypsum Recycling Working Group recommends TOC below 1.0% w/w (GtoG project, 2015a).

— Water soluble salts and pH

Water soluble salts include magnesium, sodium, potassium and chloride. These salts can be found in all types of gypsum, and therefore they are not particularly linked to the use of RG. However, a high content of salts can be due to high amounts of residual paper (GtoG project, 2015b). The only sample that presented a high TOC content (RG-01), also showed a high sodium (0.066% w/w) and chloride (0.124% w/w) content. On the other hand, the pH value complied in all cases.

The presence of soluble salts affects the paper bonding in plasterboard production. This is due to the migration of salts to the interface between the paper and the gypsum core, during the drying of plasterboard in drying kilns. These potential deposits of salts could cause the detachment of paper from the gypsum core during installation, particularly when plasterboard is exposed to high moisture (Henkels & Gaynor, 1996).

— Toxicological parameters

Toxicological parameters are related to potential heavy metal trace elements in the gypsum feedstock. Table 4.3 shows the relevant parameters part of the GtoG guidelines on RG quality criteria. It is

worthwhile mentioning that these threshold values are considered by the gypsum industry as a starting point, to be redefined for the case of RG (GtoG project, 2015a).

In this study, 100% of GY_{BAU} and 69% of GY_{RG} samples complied with the GtoG guidelines. One sample (RG-04) had a high content of lead, nickel and zinc (see Table 4.3), of unknown origin. Three samples (RG-01, RG-05 and RG-11) exceeded the nickel content. In order to further investigate these results, Institut Frenesius (SGS) conducted a second analysis on eight samples of feedstock, which resulted on values of nickel below the threshold (in samples which nickel content varied between <0.01 and >10.00 in the GtoG analysis). Discrepancy between the results suggests that further investigation is needed on the procedures and testing methods for trace elements (GtoG project, 2015a).

4.3.2. *Plasterboard: business-as-usual versus plasterboard with increased RG content*

Table 4.2, Fig. 4.2 and Fig. 4.3 show information on the average results obtained for the physical and mechanical characterization of plasterboard samples.

Table 4.2. Physical and mechanical characterization of plasterboard samples

Parameter	Unit	EN 520 ^a	PB _{BAU}				PB _{RG}			
			M	SD	Min	Max	M	SD	Min	Max
Flexural strength (Longitudinal)	N	≥550	606.67	24.48	577.00	631.00	587.57	27.91	548.00	619.00
Flexural strength (Transversal)	N	≥210	229.83	10.91	215.00	245.00	249.14	48.20	217.00	353.00
Surface water absorption (Face)	g/m ²	≤300 ^b	181.83	18.51	160.00	212.00	193.43	31.64	166.00	262.00
Surface water absorption (Back)	g/m ²	-	287.83	174.45	157.00	585.00	205.14	37.46	179.00	276.00
Density	kg/m ³	≥600	701.67	30.55	644.00	732.00	693.43	24.39	663.00	724.00
Surface hardness	mm	-	16.50	2.81	11.00	19.00	12.71	3.35	10.00	18.00

^a Reference standard EN 520, requirement for type A, 12.5 mm

^b Different levels depending on the water absorption class (H1, H2, H3). H3 is here considered.

M: mean value; SD: standard deviation; Min: minimum; Max: maximum.

Further details on the properties of PB_{BAU} and PG_{RG} can be found in “Plasterboard: physical and mechanical properties” section.

Fig. 4.2. Detailed values per sample on the flexural strength and density. Samples labelled as PB_BAU-No are part of PB_{BAU}. PB_{RG} includes samples labelled as PB_RG-No. The figure also draws the minimum requirement established by the European Standard EN 520 (CEN, 2009), for gypsum plasterboard type A, 12.5 mm.

Fig. 4.3. Water absorption per sample. Samples labelled as PB_BAU-No are part of PB_{BAU}. PB_{RG} includes samples labelled as PB_RG-No. The figure also draws the minimum requirement established by the European Standard EN 520 (CEN, 2009), for gypsum plasterboard type A, 12.5 mm.

— Mechanical characterization

Overall, the flexural strength of PB_{RG} was 3% reduced (longitudinal) and 8% increased (transversal) compared to PB_{BAU} reference values (Table 4.2). In six of the seven PB_{RG} samples (86%) flexural strength (both transversal and longitudinal) was above the EN 520 requirements (Longitudinal: 550 N, Transversal: 210 N, see Fig. 4.2), being the flexural strength longitudinal of PB-RG-9 slightly below the relevant requirement (548 N). Nevertheless, it could not be proved that the reduction of flexural

strength longitudinal was caused by the higher amount of RG. Moreover, it is considered feasible to increase the strength with minor changes in the process (GtoG project, 2015b).

— Physical characterization

Three physical properties were analysed as described in “Plasterboard: physical and mechanical properties” section: density, surface water absorption and surface hardness. In average, PB_{RG} density was about 1% lower than PB_{BAU} density. On the contrary, the minimum PB_{RG} density value (663.00 kg/m³, which corresponded to PB_{RG} -8, see Table 4.2) resulted 3% higher than the minimum PB_{BAU} value (644 kg/m³, which corresponded to PB_{BAU} -3, see Table 4.2). In any case, the results were well above the EN 520 requirement. This variability was mainly attributed to adjustments of the line speed during the manufacturing trials (GtoG project, 2015b).

Regarding surface water absorption (face), all samples complied with EN 520 requirements, and were around 0.6% higher for the case of PB_{RG} (see Table 4.2). A stricter water absorption class (H2) requires surface water absorption values below 220 g/cm², which is also fulfilled by 86% of the PB_{RG} samples (further details in Fig. 4.3). On the other hand, the average surface water absorption (back) decreased from 287.83 g/m² (PB_{BAU}) to 205.14 g/m² (PB_{RG}). These differences were attributed to the different formula and batch tested (GtoG project, 2015b).

With respect to surface hardness, PB_{RG} values were around 30% higher than those from PB_{BAU} . Surface hardness is characterised by the diameter of the depression produced in the surface of the plasterboard. Note that higher measured diameter means fewer impact resistance of the board. Although there is no minimum EN 520 requirement for type A plasterboard, there is an additional requirement for gypsum plasterboard type I (with enhanced surface hardness). This requirement entails diameters not greater than 15 mm, which was fulfilled by 70% of the PB_{RG} samples (in comparison with 14% of PB_{BAU}).

4.4. Conclusions

The present work has analysed data from testing gypsum feedstock (business-as-usual and recycled gypsum, RG) as well as gypsum plasterboard (type A, 12.5 mm) with up to 30% of RG content. The results have been discussed according to the existing voluntary guidelines on RG quality criteria for the gypsum industry (for the case of gypsum feedstock) and the European standard EN-520 (for the case of gypsum plasterboard).

With respect to gypsum feedstock, the GtoG guidelines on quality criteria were fulfilled by 56% of the RG samples. Most of these parameters can be typically managed by the deconstruction-recycling value chain (e.g. free moisture, total organic carbon, toxicological parameters), by applying effective deconstruction processes (i.e. dismantling, separate collection), and adequate recycling procedures and equipment (i.e. sorting operations prior to waste processing, equipment with high output of paper waste). In any case, technical parameters should be adapted to the specifics of each plant (e.g. particle size, purity) and values should be periodically monitored.

As regards the tested gypsum plasterboard with increased RG content (between 17 and 28%), 86% of the samples have shown compliance with the mechanical and physical requirements for plasterboard type A, 12.5 mm, in accordance to the European Standard EN-520. Moreover, the results are compared with those obtained from business-as-usual plasterboard. Variability of the results are mainly attributed to non-permanent process adjustments and the different formula and batch tested, which limit the outline of broader conclusions.

Overall, this analysis provides the basis for future studies on RG quality criteria, the use of RG in additional plasterboard types as well as the examination of higher RG reincorporation rates.

Table 4.3. Toxicological parameters

Parameter	Unit	GtoG project guidelines ^a	GY-F- 01	GY-F- 02	GY-F- 03	GY-M- 01	GY-M- 02	GY-M- 03	GY-M- 04	GY-R- 01	RG-02	RG-03	RG-04	RG-05	RG-06	RG-07	RG-08	RG-09	RG-10	RG-11	RG-12	RG-13
As	mg/kg	<4.0	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21
Be	mg/kg	<0.7	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Pb	mg/kg	<22.0	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	130.40	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18
Cd	mg/kg	<0.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr	mg/kg	<25.0	<0.01	1.42	<0.01	<0.01	0.85	<0.01	0.78	1.39	5.97	1.37	4.85	3.47	2.06	1.10	2.03	1.79	2.34	5.94	1.22	<0.02
Co	mg/kg	<4.0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	2.61	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cu	mg/kg	<14.0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	4.59	<0.01	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	4.13	<0.02
Mn	mg/kg	<200.0	16.10	53.40	52.80	18.80	43.80	17.40	62.20	52.83	33.90	14.82	56.10	50.60	26.20	21.10	25.40	24.00	26.08	52.80	10.24	20.40
Ni	mg/kg	<13.0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	7.52	12.30	7.64	30.70	31.40	7.91	8.51	10.40	8.60	2.88	31.60	11.30	11.10
Hg	mg/kg	<1.3	0.20	0.43	0.39	<0.05	<0.05	<0.05	<0.05	0.08	0.23	<0.05	0.21	0.21	0.28	0.29	0.29	0.31	0.29	0.21	<0.05	<0.05
Se	mg/kg	<16.0	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37	<0.37
Te	mg/kg	<0.3	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Tl	mg/kg	<0.4	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
V	mg/kg	<26.0	4.11	2.74	1.03	2.96	3.11	4.03	5.44	4.37	7.36	6.07	4.58	4.61	4.50	3.54	3.99	4.32	5.09	7.42	3.70	5.29
Zn	mg/kg	<50.0	4.30	15.30	16.90	4.19	4.31	3.94	5.32	6.39	29.54	39.52	52.90	31.29	18.41	18.31	13.96	17.24	16.67	43.11	16.02	13.68
Asbestos	yes/no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
R index	<0.5	<0.5	-	-	<0.02	-	-	<0.05	<0.07	-	-	-	<0.14	<0.17	<0.04	<0.04	<0.05	<0.05	<0.04	<0.08	<0.06	<0.07

^a In accordance with (GtoG project, 2015d). Highlighted in grey the values that exceed the GtoG project guidelines

References

- Beckert, J. (1990). Comparison of natural gypsum and FGD gypsum: studies for a comparative assessment of the health impact of natural gypsum and FGD gypsum from coal-fired power plants with a view to their use in the manufacture of building materials. (V. T.-W. S. Essen VGB-Kraftwerkstechnik GmbH, Ed.).
- Bundesverband der Gipsindustrie e.V. (2013). Recycled gypsum (RC-gypsum). Initial test for recycling plants, quality management, quality requirements and analysis methods. Retrieved 4 May 2016, from http://www.gips.de/wp-content/uploads/downloads/2014/03/Anlage-1a_Gipsrecycling_engl.pdf
- CEN. EN 520:2004+A1. Gypsum plasterboards - Definitions, requirements and test methods (2009).
- Chandara, C., Azizli, K. A. M., Ahmad, Z. A., & Sakai, E. (2009). Use of waste gypsum to replace natural gypsum as set retarders in portland cement. *Waste Management*, 29(5), 1675–9. <http://doi.org/10.1016/j.wasman.2008.11.014>
- Ding, G. K. C. (2008). Sustainable construction-The role of environmental assessment tools. *Journal of Environmental Management*, 86(3), 451–464. <http://doi.org/10.1016/j.jenvman.2006.12.025>
- GtoG project. (2013a). Life+ Gypsum to Gypsum (GtoG) project ‘From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry’ LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4191
- GtoG project. (2013b). DA1: Inventory of current practices LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from <http://gypsumtogypsum.org/documents/deliverable-a1-report-on-current-practices.pdf>
- GtoG project. (2015a). DC2: Protocol of action B2.2: Quality criteria for recycled gypsum, technical and toxicological parameters LIFE11 ENV/BE/001039. Retrieved 13 November 2015, from <http://gypsumtogypsum.org/documents/quality-criteria-for-recycled-gypsum-technical-and-toxicological-parameters.pdf>
- GtoG project. (2015b). DB4: Report of Production Process Parameters LIFE11 ENV/BE/001039. Retrieved 9 November 2015, from <http://gypsumtogypsum.org/documents/report-on-production-process-parameters.pdf>
- Henkels, P. J., & Gaynor, J. C. (1996). Characterizing synthetic gypsum for wallboard manufacture. *ACS Division of Fuel Chemistry, Preprints*, 41(2), 569–574.
- Jang, Y.-C., & Townsend, T. (2001). Sulfate leaching from recovered construction and demolition debris fines. *Advances in Environmental Research*, 5(3), 203–217. [http://doi.org/10.1016/S1093-0191\(00\)00056-3](http://doi.org/10.1016/S1093-0191(00)00056-3)
- Jiménez-Rivero, A., & García-Navarro, J. (2016). Indicators to Measure the Management Performance of End-of-Life Gypsum: From Deconstruction to Production of Recycled Gypsum. *Waste and Biomass Valorization*, 1–15. article. <http://doi.org/10.1007/s12649-016-9561-x>
- Jiménez Rivero, A., De Guzmán Báez, A., & García Navarro, J. (2015). Gypsum Waste: Differences across Ten European Countries. *International Journal of Sustainability Policy and Practice*, 11(4), 1–9.
- Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources, Conservation and Recycling*, 108, 171–181. <http://doi.org/10.1016/j.resconrec.2016.01.014>
- Kuttah, D., & Sato, K. (2015). Review on the effect of gypsum content on soil behavior. *Transportation Geotechnics*. <http://doi.org/10.1016/j.trgeo.2015.06.003>
- Plaza, C., Xu, Q., Townsend, T., Bitton, G., & Booth, M. (2007). Evaluation of alternative landfill cover soils for attenuating hydrogen sulfide from construction and demolition (C&D) debris landfills. *Journal of Environmental Management*, 84(3), 314–322. <http://doi.org/10.1016/j.jenvman.2006.06.001>
- Roskill. (2014). Gypsum and Anhydrite: Global Industry Markets and Outlook (Eleventh).

- Suárez, S., Roca, X., & Gasso, S. (2016). Product-specific life cycle assessment of recycled gypsum as a replacement for natural gypsum in ordinary Portland cement: application to the Spanish context. *Journal of Cleaner Production*, 117, 150–159.
<http://doi.org/10.1016/j.jclepro.2016.01.044>
- The Council of the European Union. (2003). Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex to Directive 1999/31/EC (2003/33/EC). *Official Journal of the European Communities*, L 11/27-11/49.
- Venta, G. J. (1997). Life cycle analysis of gypsum board and associated finishing products.
- VGB. VGB-M 701e. Instruction Sheet Analysis of Analysis of FGD Gypsum FGD gypsum (2008).
- WRAP and Environmental Resources Management Ltd (ERM). (2008). Technical Report: Life Cycle Assessment of Plasterboard.
- WRAP, & BSI. (2013). PAS 109:2013. Specification for the production of reprocessed gypsum from waste plasterboard. Retrieved 4 May 2016, from
[http://www.wrap.org.uk/sites/files/wrap/PAS109 \(2013\).pdf](http://www.wrap.org.uk/sites/files/wrap/PAS109%20(2013).pdf)
- WRAP, & Environment Agency. (2013). Quality Protocol. Gypsum. End of waste criteria for the production and use of recycled gypsum from waste plasterboard.

5 END-OF-LIFE CASE STUDIES ANALYSIS

CHAPTER OVERVIEW

In the construction sector, end-of-life (EoL) processes such as building deconstruction or conventional demolition commonly determine whether the material flows cycle is closed. In this context, increased knowledge on the EoL processes is considered vital for enabling stakeholders to make better informed decisions on each process. In this chapter, key performance indicators (KPIs) were used to monitor the GtoG pilot projects, with the aim to identify the ideal conditions to produce RG from EoL gypsum.

Published as

Jiménez-Rivero, A., & García-Navarro, J. (2016). Indicators to Measure the Management Performance of End-of-Life Gypsum: From Deconstruction to Production of Recycled Gypsum. *Waste and Biomass Valorization*, 1–15. doi:10.1007/s12649-016-9561-x⁷

Main research questions addressed and relation to other chapters

	Research question (and related specific objective in parentheses)	Brief answer and →Relation with other chapters
<div> <div>Chapter 1. Gypsum waste generation and management</div> <div>Chapter 2. Life cycle energy and material flows</div> <div>Chapter 3. Factors influencing post-consumer gypsum recycling</div> <div>PART II: MACRO-LEVEL</div> </div>	What conditions should be met during deconstruction and processing of gypsum waste to produce quality recycled gypsum? (O5)	<p>The ideal conditions to produce quality RG from EoL gypsum are derived from the best level of performance of the performance indicators. These conditions refer to two processes (deconstruction and recycling), eight sub-processes (audit, dismantling, traceability, transport, reception, storage, processing and RG quality) and four categories (technical, social, economic and environmental). Examples of ideal conditions are the existence of an effective pre-deconstruction audit and the absence of impurities in the gypsum waste load.</p> <p>→ The best practices for the management of EoL gypsum in Chapter 6 influence the achievement of the indicators' best level of performance as summarized in Table 6.2 in Chapter 6.</p>
<div> <div>Chapter 4. Physical and mechanical characterization</div> <div>Chapter 5. End-of-life case studies analysis</div> <div>Chapter 6. Best practices in the end-of-life stage</div> <div>PART III: MICRO-LEVEL</div> </div>		

⁷ The chapter is also based on:

Jiménez-Rivero, A., García-Navarro, J., de Guzmán-Báez, A., & Rodríguez-Quijano, M. (2015). End-of-life of gypsum plasterboard: European case studies analysis. *SGEM Conference*. Vol. 1, pp. 657–664.

5.1. Introduction

Unsustainable use of resources causes environmental damages and economic risks. On the contrary, the implementation of the circular economy (European Commission, 2015a) principles along with efficient resource recovery systems (Velis, 2015) results in optimal closed-loop networks (Accorsi, Manzini, Pini, & Penazzi, 2015). In particular, high amounts of construction and demolition (C&D) waste are generated in the European Union. Recently, one report forecasted a growth of 25% by weight in the 2011-2020 period, based on Eurostat (European Commission (DG ENV), 2011). That would mean more than one billion tonnes of total C&D waste annually generated from 2020 (Eurostat, 2012b) (more than half a billion tonnes excluding excavation material (European Commission (DG ENV), 2011)). Such urban mine, if properly managed, will produce valuable secondary resources.

Gypsum products are classified under the code 17 08 02 in the European list of wastes (The Commission of the European Communities, 2000), as part of the broader category on C&D waste (code 17). The gypsum fraction is currently estimated in 0.2-0.4% by weight (European Commission (DG ENV), 2011) of the total C&D waste. Although it represents a small percentage, gypsum recycling enhances resource efficiency, prevents the emissions of hydrogen sulphide (H_2S) and methane (CH_4) from landfills (Jiménez Rivero et al., 2016), and contributes to meet the European targets on C&D waste recovery (European Parliament and the Council of the European Union, 2008). In terms of CO_2eq , the difference between a zero and a high recycling case (0% and 93.6% of gypsum plasterboard being recycled, respectively) avoided 13.5% $kg\ CO_2eq/m^2$ (Jiménez Rivero et al., 2016). Moreover, gypsum products are very appropriate for closed-loop recycling, because the raw material calcium sulphate dehydrate ($CaSO_4 \cdot 2H_2O$) can repeatedly change its properties through a reversible hydration reaction. In the end-of-life (EoL) stage, recyclable gypsum waste (GW) mainly consists of plasterboard (around 81% of gypsum products were consumed in 2012 (Eurostat - Prodcom, 2013a)), gypsum blocks and plaster ceilings (Jiménez Rivero et al., 2015). Examples of non-recyclable GW are those bonded to insulation materials or finished with lead (Pb) based paints (GtoG project, 2015a).

The EoL stage of a construction product starts when it does not provide any further functionality (European Committee for Standardization (CEN), 2013). At this stage, demolition waste is generated, which can be either recyclable or non-recyclable waste. Recyclable demolition waste is usually strip-out waste resulting from deconstruction (also known as selective demolition and selective dismantling works). Among the life cycle stages, the EoL determines the end route of products (i.e. re-use, recycling, recovering or landfilling). In order to achieve closed-loop recycling, deconstruction (instead of conventional demolition), transport to waste processing and processing need to be well managed. Therefore, increased attention to EoL products management is considered vital to foster the production of recyclable GW and thus ensure the quality of recycled gypsum (RG).

Increased knowledge on this stage enables stakeholders to take better informed decisions that affect material flows cycle. Indicators may assist in this task, as they support data acquisition and monitoring of actions through quantitative, qualitative or descriptive information about an item or process (García Navarro, Maestro Martínez, Huete Fuertes, & García Martínez, 2009). In particular, key performance

indicators (KPIs) measure progress against targets, provide decision-making information, detect possibilities of improvement and monitor changes over time (USAID, 2010).

A number of studies have explored the use of indicators in the construction sector. For example, indicators have been utilized to describe the environmental performance of the sector (Toller, Carlsson, Wadeskog, Miliutenko, & Finnveden, 2013), analyse the contribution of materials to the overall environmental performance of office buildings (Dimoudi & Tompa, 2008), compare tools for building assessment (Srinivasan, Ingwersen, Trucco, Ries, & Campbell, 2014) or describe construction waste generation in residential constructions (Villoria Sáez et al., 2014). Indicators specifically related to the EoL stage were applied to estimate the amount of demolition waste generated on-site (in residential and non-residential demolition and refurbishment) (Mália, de Brito, Pinheiro, & Bravo, 2013), evaluate environmental impacts of construction waste in different management scenarios (Ortiz, Pasqualino, & Castells, 2010) or analyse the effectiveness C&D waste management (H. Yuan, 2013b). Recently, Akinade et al proposed an indicator that measures the degree of deconstructability during the design stage (Akinade et al., 2015), an interesting approach to plan waste recovery from the early stages of construction projects.

This is the first study to our knowledge to explore the monitoring of EoL gypsum at European level, from building deconstruction to GW processing, with the aim of obtaining RG for reincorporation into the manufacturing process. To this end, an analytical framework is defined, consisting of 44 monitoring parameters and 17 selected KPIs associated to the current best level of performance (denoted as best practice indicators, BPIs). This monitoring framework measures the performance and progress towards better EoL gypsum management practices, with the aim of obtaining quality RG (i.e. RG that complies with certain quality criteria, as detailed in “Deconstruction” section, for reincorporation into the manufacturing process).

5.2. Development of indicators for EoL gypsum management

The approach consisted of five phases as described in Fig. 5.1. In the first phase, EoL processes were identified and grouped according to the stakeholder that is commonly responsible of each EoL process (see Fig. 5.2):

Fig. 5.1. Flow chart illustrating the procedure for developing BPIs for EoL gypsum. T=technical, E=environmental, S=social, Ec=economic. KPI=key performance indicator. BPI=best practice indicator.

- Deconstruction (D), including audit, dismantling, traceability, transport of GW (processes commonly managed by the deconstruction company).
- Processing, covering recycling (R) and manufacturing (M), including reception, storage, processing operations and RG quality (process commonly managed by the gypsum recycler and/or manufacturer).

This classification enables the development of specific indicators per process and thus precise parameters, which facilitate their use and individual evaluation for a more effective analysis. The associated monitoring parameters and indicators encompass technical (T), environmental (E), social (S), economic (Ec) aspects. These initials (i.e. D, R, M and T, E, S, Ec) are used for ease of identification. For example, an indicator entitled DT1 relates to the deconstruction process, and assesses a technical aspect. In addition, the related sub-process can be found in Table 5.1.

Monitoring parameters and indicators were defined in phase II. While monitoring parameters enable data collection on-site, indicators combine relevant parameters to present information in a comparable manner. Parameters were extracted from a report on current practices on gypsum recycling (GtoG project, 2013a). Such GtoG report provides insight on the legal and regulatory framework on GW management as well as the situation regarding building construction and dismantling of gypsum-based systems, gypsum recycling and RG reincorporation. The GtoG project produced 14 additional indicators, which means a total of 37 indicators to monitor the pilot projects (GtoG project, 2015b). These additional indicators are not included within the scope of this article as they are beyond the EoL

stage and are to be considered within the product stage (European Committee for Standardization (CEN), 2013).

Fig. 5.2. Life cycle of gypsum products in a circular economy. Highlighted in grey, the EoL stage and EoL processes needed to achieve closed-loop recycling. RG: recycled gypsum; GW: gypsum waste

Once monitoring indicators are defined, application and synthesis (Phase III) were carried out by using them in five pilot projects set in four national contexts: Belgium, France, Germany and the United Kingdom (see Section 5.6. “Monitoring of European pilot projects”). Three Excel spreadsheets were developed to be filled out on-site, two for EoL processes (deconstruction and processing) and an additional one to collect data on RG quality criteria (data collection performed by manufacturers in this study. However, such criteria might be tested by recyclers or manufacturers or both). Hereunder Fig. 5.3 shows a fragment of the spreadsheet for the pilot projects on processing, technical monitoring parameters.

Parameters for the technical indicators		Value	Unit
Quality check data			
Gypsum waste received - GW			t
Gypsum waste rejected - GW _r			t
Wet Gypsum Waste received - GW _w			t
Presence of...	Plastics and foils (high/low/none)		-
	Insulation materials (high/low/none)		-
	Steel rails and bars (high/low/none)		-
	Wood (high/low/none)		-
	Other impurities (high/low/none)		-
Impurities manually separated			t
Reference GW density		0.40	t/m ³
Reference RG density		0.70	
GW processing			
Gypsum waste processed - GW _p			t
Output of:	Recycled gypsum - RG		t
	Paper fraction - P		t
	Metal - M		t

Fig. 5.3. Fragment of the excel spreadsheet, technical parameters for processing, used for data collection in the pilot projects.
t=tonne.

The validity of monitoring parameters and indicators was assessed in phase III in light of selected criteria as described below:

- Monitoring parameters' criteria: relevant, comprehensible to stakeholders, measurable (either qualitative or quantitative data).
- KPIs' criteria: direct (i.e. intuitively understandable), objective (i.e. unambiguous), useful for management (i.e. provides a meaningful measure of change over time and enables monitoring of changes), practical (i.e. data can be collected on a timely basis and at a reasonable cost), adequate (i.e. appropriate number of indicators) and disaggregated, as necessary (USAID, 2010).

Selected KPIs are associated to the current best level of performance (as described in “Deconstruction” section and “Processing” section and summarized in Table 5.6 in “Monitoring of European pilot projects” section). Henceforth, they are entitled best practice indicators (BPIs). In phase IV, fact sheets were developed and subjected to stakeholders' review (Fig. 5.4). A report on BPIs for deconstruction, recycling and reincorporation was then produced in the framework of the GtoG project (GtoG project, 2015b).

Visits and expert meetings were conducted during Phase V, framed in the Life+ Gypsum to Gypsum (GtoG) project “From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry”, which from 2013 have focused on promoting closed-loop gypsum recycling, thereby helping to achieve a resource efficient economy. The consortium has representation in seven European countries and includes five demolition companies, one demolition consultant, two GW recyclers, five plasterboard manufacturers and three academic institutions, led by Eurogypsum (the European Plaster and Plasterboard Manufacturers Association) (GtoG project, 2013b).

Process - Category - CODE							
Sub-process							
Code. Name of the indicator							
Description Explanation of what the indicator is measuring*.							
Evaluation method Criteria used to assess the results obtained, per sub-indicator.							
	<table border="1"> <thead> <tr> <th>Code. Name of the sub-indicator (unit)</th> <th>Code. Name of the sub-indicator (unit)</th> </tr> </thead> <tbody> <tr> <td>Monitoring parameter 1 - M_{p1} (unit)</td> <td>Monitoring parameter 3 - M_{p3} (unit)</td> </tr> <tr> <td>Monitoring parameter 2 - M_{p2} (unit)</td> <td>Monitoring parameter 4 - M_{p4} (unit)</td> </tr> </tbody> </table>	Code. Name of the sub-indicator (unit)	Code. Name of the sub-indicator (unit)	Monitoring parameter 1 - M_{p1} (unit)	Monitoring parameter 3 - M_{p3} (unit)	Monitoring parameter 2 - M_{p2} (unit)	Monitoring parameter 4 - M_{p4} (unit)
Code. Name of the sub-indicator (unit)	Code. Name of the sub-indicator (unit)						
Monitoring parameter 1 - M_{p1} (unit)	Monitoring parameter 3 - M_{p3} (unit)						
Monitoring parameter 2 - M_{p2} (unit)	Monitoring parameter 4 - M_{p4} (unit)						
Parameters							
Equation	$\text{CODE} = \frac{M_{p3} + M_{p4}}{M_{p3}}$						
	Parameters combined in an equation						
	PARCIAL RESULT						
	PARCIAL RESULT						
	RESULT						

* Footnote when further clarification is required

Fig. 5.4. Fact sheet template

5.3. Proposed best practice indicators for the end-of-life of gypsum products

A total of 23 monitoring indicators were formulated for the EoL of gypsum products, from which 17, complying with the KPIs criteria and associated to the current best level of performance, are considered as the final proposed BPIs (Table 5.1). They are grouped under 2 headings: deconstruction (“Deconstruction” section) and processing (“Processing” section).

Table 5.1. Monitoring indicators and selected indicators as BPIs for the EoL of gypsum products

Sub-process	Monitoring indicator	BPI
Audit	DT1. Effectiveness of the audit	Y
Dismantling	DT2. Effectiveness of the deconstruction process	Y
Traceability	DT3. Effectiveness of the traceability	Y
Transport	DE1. GW sent to landfill	Y
	DE2. Transport of GW emissions comparison	Y
Dismantling	DS1. Labour time comparison between techniques	N
	DS2. Productivity	N
	DS3. Training of the deconstruction team	Y
Transport	DS4. Follow-up of the waste management	Y
Audit	DEc1. Audit cost	N
Dismantling	DEc2. Plasterboard dismantling and loading cost	N
	Dec3. Gypsum block dismantling and loading cost	N
Traceability	DEc4. Cost comparison between routes	Y
Reception	RT1. Waste acceptance criteria	Y
	RT2. GW rejected	Y
Storage	RT3. Warehouse space	Y
Processing	RT4. Output materials of the recycling process	Y
	RE1. GHG emissions processing and transport	Y
	RE2. Natural gypsum saved	Y
Reception	RS1. Stakeholders' satisfaction	Y
Processing	REc1. Energy cost of the gypsum waste processing	N
RG quality	MT1. RG rejected	Y
	MT2. RG quality criteria	Y

D: deconstruction, R: recycling, M: manufacturing, T: technical, E: environmental, S: social, Ec: economic

As deconstruction is a prerequisite to implement a circular economy for construction products, demolition techniques are discouraged and therefore not explored during the pilot projects. For this reason, the difference between labour time needed to dismantle and demolish plasterboard is not considered as representative for closed-loop recycling (DS1). That is to say that, even if deconstruction is more labour intensive (Coelho & de Brito, 2011), it is fundamental to ensure the separate collection of GW. On the other hand, productivity was meant to present the square meter of gypsum-based systems dismantled, segregated and loaded per day and per worker (DS2). However, as dismantling time rely on the type of system (e.g. simple or double sided), the type of deconstruction process (e.g. manual or mechanical) and the skills of the workers, comparable data could not be obtained.

With respect to economic indicators, the cost of the pre-deconstruction audit (also known as building inventory or pre-deconstruction survey), as well as the cost of dismantling and loading, are commonly provided as an overall value including all waste fractions. On top of that, these costs are variable depending on the country under study and thus the indicators do not warrant comparability (DEc1, Dec2 and Dec3). The later also applies to the energy cost of the recycling and transport processes. This fact, together with recycler's confidential concerns, discarded REc1 from the final set of BPIs. Each indicator

is associated to a quantitative or qualitative evaluation criteria in order to show the degree of compliance with the best level of performance. Such criteria are based on the outcome from the pilot project data and current practices on gypsum recycling (GtoG project, 2013a, 2015a; 2015c; 2015d, 2015f).

5.3.1. Deconstruction

Quality RG requires proper management of C&D waste. While conventional C&D mixed waste collection reduces the possibilities to recover valuable recyclable materials, deconstruction enables maximum recovery of resources from EoL products. Deconstruction usually consists of two stages: soft-strip of reusable or recyclable materials and structural demolition, which are preceded by hazardous materials removal (CIB International Council for Research and Innovation in Building and Construction, 2014), if applicable. Table 5.2 shows the proposed indicators for deconstruction. Each of them is further described in the following sections.

Table 5.2. BPIs for deconstruction of gypsum-based systems. GW, gypsum waste; RG, recycled gypsum. DT1.1, DT2.1 and DS4.1 are qualitative indicators.

Indicator	Measurement methods	Unit
DT1		
DT1.1. Pre-deconstruction audit existence	$DT1.1 = \text{yes/no}$	-
DT1.2. Deviation GW	$DT1.2 = (GW_f - GW_g)/GW_g \times 100$	%
DT1.3. Deviation recyclable GW	$DT1.3 = (RGW_f - RGW_g)/RGW_g \times 100$	%
DT2		
DT2.1. Impurities	$DT2.1 = \text{yes/no}$	-
DT2.2. GW accepted	$DT2.2 = [(RGW_g - RGW_r)/RGW_g] \times 100$	%
DT3		
DT3.1. GW tracked	$DT3.1 = (GW_t/GW_g) \times 100$	%
DE1		
DE1.1. GW landfilled	$DE1.1 = (GW_l/GW_g) \times 100$	%
DE2		
DE2.1. Transport emissions recycling	$DE2.1 = (F_{CO2} \times GW_r \times D_r \times RT_r) / 1000$	kg CO ₂ eq
DE2.2. Transport emissions landfilling	$DE2.2 = (F_{CO2} \times GW_l \times D_l \times RT_l) / 1000$	kg CO ₂ eq
DS3		
DS3.1. Trained workers	$DS3.1 = W_t$	No.
DS4		
DS4.1. Workers appointed to follow-up	$DS4.1 = \text{yes/no}$	-
DEc4		
DEc4.1. Recycling route cost	$DEc4.1 = R + RT$	€/t
DEc4.2. Landfilling route cost	$DEc4.2 = L + LT$	€/t
Existence of a pre-deconstruction audit (yes/no)	GW generated and tracked - GW_t (t)	Roundtrips to the recycling facility - RT_r (No.)
Gypsum Waste foreseen - GW_f (t)	GW generated - GW_g (t)	Roundtrips to landfill - RT_l (No.)
Gypsum Waste generated - GW_g (t)	Gypsum Waste sent to landfill - GW_l (t)	Workers trained for the jobsite - W_t (No.)
Recyclable Gypsum Waste foreseen - RGW_f (t)	Freight transportation factor - F_{CO2} (g CO ₂ eq/tkm)	Worker(s) to follow-up the waste (No.)
Recyclable Gypsum Waste generated - RGW_g (t)	GW per roundtrip to recycling - GW_r (t)	Cost of recycling - R (€/t)
Presence of impurities in the GW load (yes/no)	GW per roundtrip to landfill - GW_l (t)	Recycling transport cost - RT (€/t)
Recyclable GW refused by the waste outlet- RGW_r (t)	Distance to recycling - D_r (km)	Cost of landfilling - L (€/t)
Recyclable GW generated- RGW_g (t)	Distance to landfilling - D_l (km)	Landfilling transport cost - LT (€/t)

DT1. Effectiveness of the audit

A pre-deconstruction audit, also known as building inventory or pre-deconstruction survey, reduces the uncertainty on what systems will be found when dismantling (Delgado et al., 2009), identifying the range of materials and products expected to be generated. In consequence, waste prediction facilitates the planning and implementation of an accurate waste management strategy, resulting in maximising the reduction, reuse, recycling and recovery options of materials, as well as the potential cost savings associated.

DT1 assesses the existence of such audit and the deviation of anticipated waste when compared to the real amounts of waste finally generated. DT1 is divided into: “DT1.1 Existence of the audit”, “DT1.2. Deviation GW” and “DT1.3. Deviation recyclable⁸ GW”. It is considered effective when DT1.1 is “yes”, DT1.2<10% and DT1.3<20%.

DT2. Effectiveness of the deconstruction process

The presence of wet GW and impurities limits its recyclability. Plastic, foils, insulation materials, steel rails and bars, wood, autoclaved aerated concrete and anhydrite are common impurities in the GW load that can be minimized through segregation and separate storage on-site.

This indicator shows the effectiveness of the dismantling processes through assessment of the amount of impurities and the percentage of wet GW. It is made up of “DT2.1 Impurities”, a qualitative sub-indicator that evaluates the existence of visual contaminants in the GW upon arrival at the recycling facility and “DT2.2. Gypsum waste accepted”, a quantitative sub-indicator that assesses the deviation between recyclable GW refused by the waste receptor because of non-compliance with the specifications and the recyclable GW transferred. If the result of DT2.1 is “no” and DT2.2. is 100%, it is considered effective.

DT3. Effectiveness of the traceability

The follow-up and tracking of waste flows through the EoL ensures that waste is conveyed to the appropriate treatment according to the waste hierarchy (European Parliament and the Council of the European Union, 2008), guaranteeing at the same time a high level of transparency and quality assurance in the process.

This indicator measures the deviation between the GW generated and the GW tracked, as expressed by “DT3.1. GW tracked”. Regardless the final route, to be considered effective the result must be 100%.

DE1. GW sent to landfill

Gypsum is a high-sulphate content material and, therefore, if GW is deposited in normal cells (instead of monocells) in non-hazardous landfills (The Council of the European Union, 2003), its sulphate can break down into, amongst other substances, hydrogen sulphide (H₂S). This is a colourless, flammable,

⁸According to the applicable Waste Acceptance Criteria (WAC). The agreed guidance criteria in the framework of the GtoG Life+ project can be found in the report “DB3. Guidance document with criteria for acceptance of secondary gypsum for recycling” (GtoG project, 2015a).

extremely hazardous gas associated with environmental and health effects, that even in low concentrations creates odour problems (OSHA Occupational Safety and Health Administration. US Department of Labor, 2005). Methane (CH₄) and carbon dioxide (CO₂) emissions are also generated when plasterboard is landfilled, formed during the degradation of the lining paper (Jiménez Rivero et al., 2016; WRAP and Environmental Resources Management Ltd (ERM), 2008) (when paper is deposited in mixed-waste landfills, it can be degraded by anaerobic bacteria, producing such emissions). DE1.1 describes the percentage of GW sent to landfill. The result is an indicative value as it depends on the type of GW generated, due to the fact that there are non-recyclable gypsum systems. In any case, the result of 0% demonstrates the implementation of efficient deconstruction practices.

DE2. GHG emissions from transporting the GW comparison

GW is delivered either to recovery or disposal. This indicator compares GHG emissions, in terms of kg CO₂eq, derived from transporting the GW from the jobsite to the recycling facility or landfill. The result is an indicative value, as the parameters related to the number of roundtrips depend on the deconstruction technique applied. The latter influences the GW size and shape, type of skips and the way the waste is placed inside them. DE2 is divided into “DE2.1. Recycling” and “DE2.2. Landfilling”. If the subtraction of DE2.1 from DE2.2 has a negative value, it means that the recycling route results in emission savings.

DS3. Training of the deconstruction team

Deconstruction works require skilled workers in waste handling for an efficient source separation and subsequent storage. DS3 shows whether workers trained in gypsum products dismantling, sorting and storing of GW have been appointed, in which case DS3.1 > 0 and compliance is shown.

DS4. Follow-up of the waste management

Supervising GW management entails periodic checks on the use of skips (e.g. removal of impurities) and covering skips in order to reduce potential moisture. DS4.1 shows whether a person responsible for the follow-up of the waste management including the tracking records exists. If that is the case, there is compliance.

DEc4. Cost comparison of recycling and landfilling route

DEc4 compares the cost per tonne of the recycling route with the landfill route, either direct or via transfer station, including rental of skips, loading and unloading operations, gate fee and tax. If the subtraction of “DEc4.1 Cost of recycling” and “DEc4.2 Cost of landfilling” is a negative value, this means recycling cost savings.

5.3.2. Processing

Closed-loop gypsum recycling demands high quality RG. In order to achieve the requirements, controlled processing of GW separates the gypsum from paper lining and any impurities. This stage generally comprises GW reception, storage, processing operations, RG storage and RG quality. Table 5.3 shows the proposed indicators for processing. Each of them is further described in the following sections.

Table 5.3. BPIs for GW processing

Indicator	Measurement methods	Unit
RT1		
RT1.1. Impurities ^a	$RT1.1 = (I/GW) \times 100$	%
RT1.2. Wet GW received	$RT1.2 = (GW_w/GW) \times 100$	%
RT2		
RT2.1. Rejection rate	$RT2.1 = (GW_r/GW) \times 100$	%
RT3		
RT3.1. GW volume	$RT3.1 = GW/0.40$	m ³
RT3.2. RG volume	$RT3.2 = RG/0.70$	m ³
RT4		
RT4.1. RG	$RT4.1 = (RG/GW_p) \times 100$	%
RT4.2. Paper	$RT4.2 = (P/GW_p) \times 100$	%
RT4.3. Metal	$RT4.3 = (M/GW_p) \times 100$	%
RE1		
RE1.1. Processing CO ₂ eq	$RE1.1 = [(EE \times E_e) + (EF \times E_f)]/GW_p$	kg CO ₂ eq/t
RE1.2. Transport CO ₂ eq	$RE1.2 = (F_{CO2} \times RG_{rd} \times D_r \times RT_r)/1000$	kg CO ₂ eq/t
RE2		
RE2.1. RG obtained	$RE2.1 = RG$	t
RS1		
RS1.1. GW quality	$RT1.1 \leq 2; RT1.2 \leq 10$	%
RS1.2. RG quality	$MT1.2 = RG \text{ quality criteria}$	various ^b
MT1		
MT1.1. RG rejected	$MT1.1 = (RG_r/RG) \times 100$	%
MT2		
MT2.1. Quality criteria assessment	$MT1.2 = RG \text{ quality criteria}$	various ^b
Gypsum waste received - GW(t)	Metal fraction - M (t)	Distance to reincorporation - D _r (km)
Impurities manually separated - I (t)	Gypsum waste processed - GW _p (t)	Roundtrips to reincorporation - RT _r (No.)
Wet gypsum waste received - GW _w (t)	Electricity consumption - E _e (kWh)	Freight transportation factor - F _{CO2} (g CO ₂ eq/tkm)
Gypsum waste rejected - GW _r (t)	Fuel consumption - E _f (l)	Total recycled gypsum rejected - RG _r (t)
GW reference density - 0.40 (t/m ³)	Electricity emission factor - EE (kg CO ₂ eq/kWh)	RG quality criteria - various
Recycled gypsum obtained - RG (t)	Emission intensity of Fuel -EF (kg CO ₂ equiv/l)	RG reference density - 0.70 (t/m ³)
Paper fraction - P (t)	RG per roundtrip to reincorporation- RG _{rd} (t)	

Hazardous impurities are always excluded. ^bRG quality criteria include technical and toxicological parameters. Units: mm for the particle size; %w/w for the rest of technical parameters; mg/kg for the toxicological parameters. For further information on the reference values see (GtoG Project, 2015a), section 1.1.3

RT1. Waste acceptance criteria

GW is assessed against the waste acceptance criteria (WAC) guidelines developed during the GtoG project (GtoG project, 2015c). WAC can be defined as the requirements against which the gypsum recycler assesses the waste load to ascertain if they will accept it for processing or reject it (WRAP & BSI, 2013). GW accepted by recyclers includes plasterboard, plaster ceilings, glass reinforced gypsum products, plaster powder, blocks.

This indicator evaluates the compliance with the WAC in relation to the presence of impurities and the percentage of wet waste received. It is divided into “RT1.1 Impurities” and “RT1.2 Wet gypsum waste received”. It is considered compliance when $RT1.1 \leq 2\%$ and $RT1.2 \leq 10\%$. Further details can be found in (GtoG project, 2015a).

Table 5.4. Summary table of WAC of the gypsum recyclers participating in the GtoG project and their area of coverage

		FR	BE, UK	DE
General issues	Free moisture content	Not limited	Not limited	<10% in weight
	Maximum percentage of impurities	2%	2%	2-3%
Gypsum product	Plaster ceilings and floors	✓	✓	✓
	Ceiling plaster tiles ^a	✓	✓	✗
	Glass reinforced gypsum (GRG) products	✓	✓	✓
	Moulds / cove	✓	✓	After approval
	Moulds used in foundry ^a	✓	✓	After approval
	Plaster powder	✓	✓	✓
	Plaster block	✓	✓	✓
	Honeycomb plasterboard	✓	✓	✓
	Plasterboard bonded to insulation ^b	✗	✗	✗
Finishing	Wallpaper	✓	✓	✓
	Glass fibre wallpaper and vinyl lining	✗	✓	✓
	Lead based paint	✗	✗	✗
Other	Autoclaved aerated concrete (AAC)	✗	✗	✗
	Hazardous materials, e.g. Asbestos	✗	✗	✗
	Fibreboard ^a	✓	✓	Limited
	Hardened boards	✓	✓	✗
	Cement bound boards ^a	✓	✓	✗

^aIn these cases gypsum waste isn't accepted by one of the recyclers in France. ^b Plasterboard can be recycled when it is separated from the insulation. Nevertheless, the recyclers involved in the GtoG project don't accept insulated plasterboards. An example of system that process gypsum adhered to other materials can be found in Patent WO 2011/027255 A1 "Method and plant for recycling plaster waste".

RT2. GW rejected

GW might be rejected by the gypsum recycler if the load does not comply with the WAC. Examples of non-accepted gypsum based products are those bonded to insulation materials or finished with lead (Pb) based paints. In some instances, the presence of ceiling plaster tiles, glass fibre wall panel, vinyl lining, hardened boards and cement bound boards are also not acceptable for recycling. In any case, the presence of autoclaved aerated concrete (AAC) and hazardous materials is not accepted.

RT2 assesses the rate of GW rejected by the recycler due to non-conformity with the relevant WAC, as defined in the "Guidance document with criteria for acceptance of secondary gypsum for recycling" developed in the GtoG project (GtoG project, 2015c). A rejection rate would mainly occur if high moisture content or presence of impurities is found in the load. Compliance is shown when RT2=0%. Otherwise there is a need of corrective actions.

RT3. Warehouse space

Warehouse space is needed to store the waste received as well as the resulting RG. Currently, mobile and static recycling units operate in the EU. Static recycling units are permanently located in a warehouse, while mobile recycling units periodically visit different warehouse locations to process the material (Roskill, 2014). Warehouses located close to plasterboard manufacturing plants enable environmental and economic benefits as transportation distances are minimized.

RT3 assesses the required space for storing GW (RT3.1) and RG at the recycling plant (RT3.2), based on the GW and RG reference density obtained from the GtoG pilot projects (t/m^3). A properly dimensioned covered storage facility should be set up in order to guarantee a constant GW feedstock. Based on this, this indicator gives a rough estimation of the required space for storage.

RT4. Output materials of the recycling process

Prior to waste processing, GW is hand-cleaned of impurities. Then it is loaded into the recycling unit, in which a quality control agent and an electromagnet typically remove the potential remaining impurities. Through several mechanical steps, such as grinding and sieving, the facing paper is separated from the gypsum core. Consequently there are three output streams of the recycling process: RG (up to 94% by weight), paper waste (up to 10% by weight of a mix of lining paper with gypsum residues) and metal (less than 1%) (GtoG project, 2013a).

“RT4.1. RG”, “RT4.2. Paper” and “RT4.3. Metal” present the output after waste processing. If RT4.2 is significantly low, it can be attributed to the fact that paper hasn't been properly removed, which affects the quality of the RG output (as total organic carbon content should remain below 1.5% w/w in order to comply with RG quality criteria. See MT2). Therefore, $\text{RT4.2} > 0\%$ shows compliance with the requirements.

RE1. GHG emissions processing and transport

Emissions resulting from waste processing and transportation of RG are quantified by “RE1.1. Processing CO_2eq ” and “RE1.2. Transport CO_2eq ”. The result is compared with the extraction of natural gypsum (reference value $2.033 \text{ kg CO}_2\text{eq/t}$) which has been obtained from reference data (Ecoinvent, 2012; ITB EPD, 2014). Emissions savings are obtained when the sum of RE1.1 and RE1.2 is below the reference value.

RE2. Natural gypsum saved

RE2 shows the amount of RG obtained, avoiding natural resource depletion as well as H_2S , CH_4 and CO_2 emissions from landfill disposal. It is assumed that natural gypsum saved equals to RG obtained. Natural gypsum savings are achieved when the result of RE2.1 is above zero.

RS1. Stakeholder's satisfaction

RS1.1 quantitatively assess recycler's satisfaction with the waste received. Similarly, RS1.2. shows manufacturer's satisfaction with the resulting RG. If best practices are applied, RS1.1 complies with the WAC (see RT1) and therefore the threshold of impurities (i.e. 2%) and wet GW (i.e. 10%) is met. In addition, RG quality criteria are met (see MT2).

MT1. RG rejected

MT1.1 presents the rate of RG rejected by the manufacturer due to non-compliance with the agreed quality specifications (see MT2). If best practices are applied during deconstruction and waste processing, the result is typically 0%.

MT2. RG quality criteria

RG should meet compliance with applicable quality criteria in order to be reincorporated into the manufacturing process. Existing specifications for RG are country-specific or even company-specific (Jiménez Rivero et al., 2015) and therefore different RG quality criteria are found in the European context, such as the initial test for recycling plants quality management in Germany (Bundesverband der Gipsindustrie e.V., 2013), the report on specification for the production of reprocessed gypsum from waste plasterboard in the UK (WRAP & BSI, 2013), and commercial specifications developed by gypsum recyclers, plasterboard manufacturers or Eurogypsum Member Associations. European guidelines were developed during the GtoG project (GtoG project, 2015e).

Quality criteria are also a vital component to achieve the end-of-waste (EoW) status, which means waste ceasing to be waste (Delgado et al., 2009), in accordance with article 6 of Directive 2008/98/EC (European Commission, 2015b; European Parliament and the Council of the European Union, 2008). While priority waste streams have already achieved EoW status (i.e. iron, steel, aluminum scrap, glass cullet and copper scarp), other waste fractions are being considered as possible candidates, i.e. waste-derived aggregates (Hjelmar, Van Der Sloot, Comans, & Wahlström, 2013) and GW (GtoG project, 2013b).

MT2.1 assesses RG compliance with quality criteria, in relation to technical (e.g. particle size, free moisture, purity, total organic content - TOC) and toxicological parameters (e.g. As, Be, Pb, Cd). All parameters as well as the reference values produced in the framework of the GtoG project can be found in (GtoG Project, 2015e). When parameters meet the agreed specifications, the result is “Compliance”. Otherwise, it is “Non-compliance”.

5.4. Monitoring of European pilot projects

The pilot projects covered five tertiary buildings that undergone renovation, five recycling plants and five manufacturing plants (Table 5.5). First, gypsum-based systems were audited and dismantled, using various techniques and practices in countries where deconstruction is a usual practice. Second, the generated GW was processed and then transferred as RG to manufacturers.

Processes were monitored between 2014 and 2015. In all cases, gypsum-based systems were dismantled, segregated on-site and transported to the closest recycler (see Fig. 5.5) that operates for closed-loop systems. In two of the cases (PI and PII), the recycling warehouses are adjacent to the manufacturing plants. In one case (PIV), GW was processed by a plasterboard manufacturer with a recycling unit for EoL gypsum. In the rest of the cases, recycling facilities are strategically located (e.g. close to distinct manufacturing plants). The results of the monitoring are summarized in Table 5.6. The best level of performance is met in most of the cases, as the pilot projects were implemented in countries with a culture of C&D waste recycling and hence best practices were implemented.

Fig. 5.5. Photographs of EoL processes from the pilot projects. (a) dismantling in PV, (b) segregation and separate storage on-site in PI, (c) GW reception in PIII, and (d) waste processing in PV

Table 5.5. Overview of the pilot projects

General data	Pilot projects				
	PI	PII	PIII	PIV	PV
Deconstruction location	Brussels, Belgium (BE)	Paris, France (FR)	London, United Kingdom (GB)	Levallois Perret, France (FR)	Grabben, Germany (DE)
Description	2 floors object of study, from 1990	3-storey building, from 1998	12-storey building, from 1980's	9-storey building, from 1968	5 single-storey buildings, from 1965
Type of gypsum-based system	Double-sided plasterboard partition, metallic frame, mineral wool insulation	Gypsum block partition; Double-sided plasterboard partition, metallic frame, expanded polystyrene; plasterboard ceiling, metallic frame	Plasterboard partition, metal frame, glass/rock wool insulation	Double plasterboard partition, metallic frame, glass wool insulation	Plasterboard ceiling, wooden frame, mineral wood insulation; Plasterboard laminate, metallic frame; Plasterboard partition, wooden frame, wood wool insulation
Deconstruction process	Mechanical	Manual	Manual	Manual	Manual
Recyclable GW (t)	42.94	9.38	50.00	67.52	23.64
Non-recyclable GW (t)	0.00	7.80	0.00	0.00	13.00
Distance to recycling facility (km)	64.60	39.50	199.00	86.00	150.00*
Recycling location	Kallo, BE	Vaujours, FR	Avonmouth, GB	Auneuil, FR	Werkendam, NL
Common output from recycling unit (RG/P/M%)	94/6/<1	94/6/<1	94/6/<1	unknown	>90/<10/<1
Distance to reincorporation (km)	0.00	0.00	6.60	0.00	5.00*
Manufacturing location	Kallo, BE	Vaujours, FR	Bristol, GB	Auneuil, FR	Iphofen, DE

* Assumption for Germany, where there is no gypsum recycler. Average transportation distance from (GtoG project, 2013a).

While only recyclable GW was generated in three cases (PI, PIII and PIV), non-recyclable GW was produced in PII and PV (DE1), due to the existence of gypsum-based systems glued to ceramics (in the case of gypsum blocks) and insulation (in the case of plasterboard). In such cases, the existence of a pre-deconstruction audit could not prevent the generation of non-recyclable GW. Not even in the case of PII, which achieved the required level of performance (DT1). Design for deconstruction becomes therefore an urgent need in order to minimize non-recyclable waste. Nevertheless, a pre-deconstruction audit promotes the implementation of a more precise waste management strategy, which benefits the recycling route. At present, such detailed demolition inventory is not mandatory in the UK (PIII).

Interestingly, BRE, the UK Building Research Establishment, has recently standardised a voluntary methodology for pre-demolition audits (Deloitte, 2015). On the other hand, PIV presents the highest deviation (both for recyclable and non-recyclable GW). This was due to wooden systems mistook for gypsum-based systems.

As for cost performance, the recycling route resulted in savings in three of the five pilot projects (PI, PII and PIV), mainly due to high landfill taxes (Dec4). This indicator could not be assessed in PV due to the absence of data (recycling fee was reported as confidential by the recycler). It is interesting to note that, in this exceptional case (PV), GW was sent to the Netherlands for processing because EoL gypsum recycling systems did not operate in Germany. However, this is not considered a good practice as it is known that transport distances should be kept as minimum as possible. Particularly, for the case of GW, it has been reported that GW transported equal or less than 30 km results in environmental benefits when compared with natural gypsum production (Suárez et al., 2016). In our monitoring framework, environmental impacts are estimated, in terms of CO₂eq, by DE2, which compares emissions from the recycling and the landfill routes. PIV and PV did not achieve the required performance level, as for these two cases the closest recycling facility was located far beyond the local landfill site (e.g. in PIV, landfill located 42 km away from building site; recycling facility located 86 km away).

In terms of waste processing, GW received in the recycling facilities contains neither a relevant amount of impurities (<1.5% in all cases, RT1.1) nor wet GW (RT1.2). After processing, paper waste arose in all cases (5.5% in average), which compares well with the average amount of paper output when GW contains plasterboard (GtoG project, 2013a). Accordingly, PII presented the lowest paper output, as mainly gypsum blocks were generated from deconstruction (around 55% of total GW). With regard to the total waste processed, besides the recyclable GW received from the pilot projects, additional GW was processed and sent for reincorporation (in order to provide the minimum required amount of RG to perform full scale production trials).

In total, 547.02 tonnes of natural gypsum were saved (RE2), as 100% of the RG was reincorporated into the manufacturing process in four of the cases (PI, PII, PIII and PIV). Only in one case (PV), 80% of the RG was considered as usable RG by the manufacturer. In particular, MT2 best performance level was not met, due to non-compliance with at least one of the quality criteria parameters (specific details are considered confidential by the stakeholders). In any case, it is worth mentioning that reference values regarding technical parameters (e.g. purity, free moisture) require agreements between recyclers and manufacturers at plant level, as specific needs may differ from the guidelines produced under the GtoG project (GtoG project, 2015e).

Table 5.6. Monitoring results from the pilot projects and best level of performance

BPI	Unit	Results					Best level of performance
		PI	PII	PIII	PIV	PV	
DT1		✗	✓	✗	✗	✗	
DT1.1.	-	yes	yes	no	yes	yes	DT1.1=yes; DT1.2<10.0; DT1.3<20.0
DT1.2.	%	39.7	5.8	40.0	394.7	9.2	
DT1.3.	%	39.7	12.6	40.0	246.3	69.2	
DT2		✓	✓	✓	✓	✓	
DT2.1.	-	no	no	no	no	no	DT1.2=no; DT2.2=100.0
DT2.2.	%	100.0	100.0	100.0	100.0	100.0	
DT3		✓	✓	✓	✓	✓	
DT3.1.	%	100.0	100.0	100.0	100.0	100.0	DT3.1=100.0
DE1		✓	✗	✓	✓	✗	
DE1.1.	%	0.0	45.3	0.0	0.0	35.5	DE1.1=0
DE2		✓	✓	✓	✗	✓	
DE2.1 - DE2.2.	kg CO ₂ eq	-131.3	-56.0	-1037.7	239.1	177.6	DE2.1 - DE2.2<0
DS3		✓	✓	✓	✓	✓	
DS3.1.	No.	15.0	12.0	8.0	15.0	8.0	DS3.1>0
DS4		✓	✓	✓	✓	✓	
DS4.1.	-	yes	yes	yes	yes	yes	DS4.1=yes
DEc4		✓	✓	✗	✓	-	
DEc4.1.-DEc4.2.	€/t	-80.0	-55.0	24.6	-36.7	-	DEc4<0
RT1		✓	✓	✓	✓	✓	
RT1.1.	%	0.6	1.5	1.1	0.0	0.0	RT1.1≤2.0; RT1.2≤10.0
RT1.2.	%	0.0	0.0	0.0	0.0	0.0	
RT2		✓	✓	✓	✓	✓	
RT2.2.	%	0.0	0.0	0.0	0.0	0.0	RT2.2=0
RT3		✓	✓	✓	✓	✓	
RT3.1.	m3	550.0	510.6	121.5	169.1	92.5	RT3.1+RT3.2<warehouse storage capacity
RT3.2.	m3	293.6	282.9	63.3	93.7	48.0	
RT4		✓	✓	✓	✓	✓	
RT4.2.	%	>0 ^a	>0 ^a	>0 ^a	>0 ^a	>0 ^a	RT4.2>0
RE1		-	-	-	-	-	
RE1.1.+RE1.2.		-	-	-	-	-	RE1.1.+RE1.2.<2.033
RE2		✓	✓	-	-	✓	
RE2.1.	t	205.5 ^b	198.0 ^b	-	-	78.2 ^b	RE2.1>0
RS1		✗	✓	✗	✓	✗	
RS1.1.	%	0.6/0.0	1.5/0.0	1.1/0.0	0.0/0.0	0.0/0.0	RS1.1.<2/<10; RS1.2.=C
RS1.2.	- ^c	NC	C	NC	C	NC	
MT1		✓	✓	✓	✓	✗	
MT1.1.	%	0.0	0.0	0.0	0.0	20.0	MT1.1.=0
MT2		✗	✓	✗	✓	✗	
MT1.1.	various ^d	NC	C	NC	C	NC	MT1.1.=0

✓ Best performance level achieved

✗ Best performance level did not achieve

- Not enough data or confidential to report individually

^a It is considered confidential to report in an individual manner. Average 5.5%. ^b Besides the GW received from the pilot building site, additional GW was processed and send for reincorporation. ^c C=compliance; NC=non-compliance, according to monitoring parameters as detailed in (GtoG Project, 2015e). ^d See Table 5.3 for further information on the units. Energy and emissions intensity factors (DE2) based on data published by the EEA and IEA (European Environment Agency, 2011; International Energy Agency, 2008). EU-27 average electricity emission factor from (European Environment Agency (EEA), 2008).

5.5. Conclusions

This study explored the monitoring of end-of-life (EoL) gypsum through performance indicators, with the aim of promoting a circular economy. A set of indicators is proposed, which consists of 17 key performance indicators (KPIs) associated to the current best level of performance, referred to as best practice indicators (BPIs). This monitoring framework was developed during 2014 and 2015; and benefitted from data input from five European pilot projects conducted during the same period in the framework of the Life+ GtoG project. Moreover, to verify the usefulness of BPIs, results from the pilot projects were examined. The findings suggest that BPIs can also enhance stakeholders' understanding of how to contribute to EoL gypsum management and hence set the basis that motivate improvement. Moreover, this method can be replicated to other EoL products.

BPIs are classified into two processes (i.e. deconstruction – D and recycling – R) and four categories (i.e. technical – T, social – S, economic – Ec and environmental – E), which initials are part of their abbreviated title. In addition, BPIs are associated to eight sub-processes (i.e. audit, dismantling, traceability, transport of GW, reception, storage, processing operations and RG quality). The analysis of the best level of performance enables the formulation of the ideal conditions to produce quality RG from EoL gypsum, as described below:

- A pre-deconstruction audit for gypsum systems exists, and a minimum deviation compared with the real amount and type of gypsum waste (GW) generated results, which indicates *Effectiveness of the audit (DT1)*.
- There is no presence of impurities in the GW, and as a result there is no recyclable GW refused by the recycler, which proves the *Effectiveness of the deconstruction process (DT2)*.
- All GW generated is tracked, and therefore the *Effectiveness of the traceability (DT3)* is ensured.
- There is no *GW sent to landfill (DE1)*, which enables a resource efficient economy.
- Transportation distances from deconstruction to recycling are kept as low as possible and therefore *GHG emissions from transporting the GW comparison (DE2)* (comparison between transport to recycling and landfilling) results in emissions savings.
- Trained workers are in charge of the dismantling, sorting and storing processes, which shows *Training of the deconstruction team (DS3)*.
- At least one person is appointed to *Follow-up the waste management (DS4)*.
- When performing *Cost comparison between routes (Dec4)*, recycling is favourable when compared with landfilling. This cost includes rental of skips, unloading and loading operations, gate fee and tax.
- GW at the recycling plant complies with the recyclers' *Waste acceptance criteria (RT1)* thus there is no *GW rejected (RT2)* nor sent to landfill.
- A properly dimensioned *Warehouse space (RT3)* is set up in order to guarantee a constant feedstock, avoiding further presence of impurities and moisture content at the same time.
- Paper is generated as an *Output material of the recycling process (RT4)* when plasterboard is present at the waste load.

- *GHG emissions from waste processing and transport (RE1)* are lower than those generated from the extraction of natural gypsum.
- The use of RG in the manufacturing of new plasterboard saves extraction of raw materials, which implies *Natural gypsum saved (RE2)*.
- Compliance with WAC and RG quality criteria is met, which promotes *stakeholders' satisfaction (RS1)* with the recycling process.
- RG complies with the agreed *RG Quality criteria (MT2)* thus there is no *RG rejected (MT1)*.

References

- Accorsi, R., Manzini, R., Pini, C., & Penazzi, S. (2015). On the design of closed-loop networks for product life cycle management: Economic, environmental and geography considerations. *Journal of Transport Geography*, 48, 121–134. <http://doi.org/10.1016/j.jtrangeo.2015.09.005>
- Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources, Conservation and Recycling*, 105, 167–176. <http://doi.org/10.1016/j.resconrec.2015.10.018>
- Bundesverband der Gipsindustrie e.V. (2013). Recycled gypsum (RC-gypsum). Initial test for recycling plants, quality management, quality requirements and analysis methods. Retrieved 4 May 2016, from http://www.gips.de/wp-content/uploads/downloads/2014/03/Anlage-1a_Gipsrecycling_engl.pdf
- CIB International Council for Research and Innovation in Building and Construction. (2014). Barriers for Deconstruction and Reuse / Recycling of Construction Materials. (U. S. A. Shiro Nakajima, Building Research Institute, Japan Mark Russell, University of New Mexico, Ed.). CIB Publication 397.
- Coelho, A., & de Brito, J. (2011). Economic analysis of conventional versus selective demolition—A case study. *Resources, Conservation and Recycling*, 55(3), 382–392. <http://doi.org/10.1016/j.resconrec.2010.11.003>
- Delgado, L., Sofia-Catarino, A., Eder, P., Litten, D., Luo, Z., & Villanueva, A. (2009). End of waste criteria. Final Report.
- Deloitte. (2015). Construction and Demolition Waste management in United Kingdom. V3 - December 2015. Retrieved 4 May 2016, from http://ec.europa.eu/environment/waste/studies/deliverables/CDW_UK_Factsheet_Final.pdf
- Dimoudi, A., & Tompa, C. (2008). Energy and environmental indicators related to construction of office buildings. *Resources, Conservation and Recycling*, 53(1–2), 86–95. <http://doi.org/10.1016/j.resconrec.2008.09.008>
- Ecoinvent. (2012). Ecoinvent v2.2 Life Cycle Inventory (LCI) database, Gypsum, mineral, at mine/CH S. Retrieved 5 June 2015, from <http://www.ecoinvent.org/>
- European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy (2015). Retrieved from http://ec.europa.eu/environment/circular-economy/index_en.htm
- European Commission. Proposal for a Directive of the European Parliament and of the Council amending Directive 1999/31/EC on the landfill of waste, Pub. L. No. COM(2015) 594 final, 2015/0274 (COD) (2015).
- European Commission (DG ENV). (2011). Service Contract on Management of Construction and Demolition Waste - SR1. Final Report Task 2. A project under the Framework contract ENV.G.4/FRA/2008/0112. Retrieved 17 January 2016, from http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf

- European Committee for Standardization (CEN). EN 15804:2012+A1:2013. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (2013).
- European Environment Agency. (2011). Specific CO₂ emissions per tonne-km and per mode of transport in Europe, 1995-2011 — European Environment Agency (EEA). Retrieved 17 January 2016, from <http://www.eea.europa.eu/data-and-maps/figures/specific-co2-emissions-per-tonne-2>
- European Environment Agency (EEA). (2008). Trends in energy GHG emission factors and % renewable electricity (EU-27). Retrieved 17 January 2016, from <http://www.eea.europa.eu/data-and-maps/figures/trends-in-energy-ghg-emission>
- European Parliament and the Council of the European Union. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Retrieved 12 April 2015, from <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:en:PDF>
- Eurostat. (2012). Generation of waste, NACE Rev. 2. Code F, Construction. Total Waste. 2012. Last update: 23-07-2015. Retrieved 4 April 2016, from <http://ec.europa.eu/eurostat>
- Eurostat - Prodcom. (2013). NACE Rev. 2. Statistics on the production of manufactured goods, total volume annual. 2013. Retrieved 4 April 2016, from <http://ec.europa.eu/eurostat/web/prodcom>
- García Navarro, J., Maestro Martínez, L., Huete Fuertes, R., & García Martínez, a. (2009). Establecimiento de indicadores de sostenibilidad para entornos degradados: el Valle minero de Laciana (León, España). *Informes de La Construcción*, 61, 51–70. <http://doi.org/10.3989/ic.08.022>
- GtoG project. (2013a). DA1: Inventory of current practices LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from <http://gypsumtogypsum.org/documents/deliverable-a1-report-on-current-practices.pdf>
- GtoG project. (2013b). Life+ Gypsum to Gypsum (GtoG) project ‘From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry’ LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4191
- GtoG project. (2015a). DB1. European Handbook on best practices in deconstruction techniques LIFE11 ENV/BE/001039. Retrieved 4 May 2016, from <http://gypsumtogypsum.org/documents/db1-european-handbook-on-best-practices-for-controlled-deconstruction-of-drywall-systems-in-demolitionrefurbishment-sites-as-a-basis-for-a-new-european-standard-on-deconstruction-of-lightweight-syst.pdf>
- GtoG project. (2015b). DC1. Report on best practice indicators for deconstruction, recycling and reincorporation LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/news/newsarchive2015/documents/20150715_gtog.pdf
- GtoG project. (2015c). DB3: Guidance document with criteria for acceptance of secondary gypsum for recycling LIFE11 ENV/BE/001039. Retrieved 4 April 2016, from <http://gypsumtogypsum.org/documents/guidance-document-with-criteria-for-acceptance-of-secondary-gypsum-for-recycling.pdf>
- GtoG project. (2015d). DA2: Inventory of best practices LIFE11 ENV/BE/001039. Retrieved 17 July 2016, from <http://gypsumtogypsum.org/documents/da2-inventory-of-best-practices.pdf>
- GtoG project. (2015e). DC2: Protocol of action B2.2: Quality criteria for recycled gypsum, technical and toxicological parameters LIFE11 ENV/BE/001039. Retrieved 13 November 2015, from <http://gypsumtogypsum.org/documents/quality-criteria-for-recycled-gypsum-technical-and-toxicological-parameters.pdf>
- GtoG project. (2015f). DB4: Report of Production Process Parameters LIFE11 ENV/BE/001039. Retrieved 9 November 2015, from <http://gypsumtogypsum.org/documents/report-on-production-process-parameters.pdf>

- Hjelmar, O., Van Der Sloot, H. a., Comans, R. N. J., & Wahlström, M. (2013). EoW criteria for waste-derived aggregates. *Waste and Biomass Valorization*, 4(4), 809–819.
<http://doi.org/10.1007/s12649-013-9261-8>
- International Energy Agency. (2008). *Worldwide Trends in Energy Use and Efficiency. Key Insights from IEA Indicator Analysis*. Paris: IEA Publications.
- ITB EPD. (2014). *Environmental Product Declaration Gypsum plasterboard*. No 025/2014. Poland.
- Jiménez Rivero, A., De Guzmán Báez, A., & García Navarro, J. (2015). Gypsum Waste: Differences across Ten European Countries. *International Journal of Sustainability Policy and Practice*, 11(4), 1–9.
- Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources, Conservation and Recycling*, 108, 171–181. <http://doi.org/10.1016/j.resconrec.2016.01.014>
- Mália, M., de Brito, J., Pinheiro, M. D., & Bravo, M. (2013). Construction and demolition waste indicators. *Waste Management & Research : The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 31(3), 241–55.
<http://doi.org/10.1177/0734242X12471707>
- Ortiz, O., Pasqualino, J. C., & Castells, F. (2010). Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. *Waste Management (New York, N.Y.)*, 30(4), 646–54. <http://doi.org/10.1016/j.wasman.2009.11.013>
- OSHA Occupational Safety and Health Administration. US Department of Labor. (2005). *Hydrogen Sulfide OSHA FactSheet*. DSG 10/2005. Retrieved 17 January 2016, from https://www.osha.gov/OshDoc/data_Hurricane_Facts/hydrogen_sulfide_fact.pdf
- Roskill. (2014). *Gypsum and Anhydrite: Global Industry Markets and Outlook (Eleventh)*.
- Srinivasan, R. S., Ingwersen, W., Trucco, C., Ries, R., & Campbell, D. (2014). Comparison of energy-based indicators used in life cycle assessment tools for buildings. *Building and Environment*, 79, 138–151. <http://doi.org/10.1016/j.buildenv.2014.05.006>
- Suárez, S., Roca, X., & Gasso, S. (2016). Product-specific life cycle assessment of recycled gypsum as a replacement for natural gypsum in ordinary Portland cement: application to the Spanish context. *Journal of Cleaner Production*, 117, 150–159.
<http://doi.org/10.1016/j.jclepro.2016.01.044>
- The Commission of the European Communities. Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 74/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of C (2000). *European union: Official Journal of the European union*. Retrieved from <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32000D0532&from=EN>
- The Council of the European Union. (2003). Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex to Directive 1999/31/EC (2003/33/EC). *Official Journal of the European Communities*, L 11/27-11/49.
- Toller, S., Carlsson, A., Wadeskog, A., Miliutenko, S., & Finnveden, G. (2013). Indicators for environmental monitoring of the Swedish building and real estate management sector. *Building Research & Information*, 41(2), 146–155. <http://doi.org/10.1080/09613218.2012.749747>
- USAID. (2010). *Selecting Performance Indicators. Supplemental reference to the Automated Directive System (ADS) Chapter 203*. Retrieved 4 April 2016, from http://pdf.usaid.gov/pdf_docs/pnadw106.pdf
- Velis, C. A. (2015). Circular economy and global secondary material supply chains. *Editorial. Waste Management & Research*, 33(5), 389–391. <http://doi.org/10.1177/0734242X15587641>
- Villoria Sáez, P., del Río Merino, M., Porras-Amores, C., & San-Antonio González, A. (2014). Assessing the accumulation of construction waste generation during residential building construction works. *Resources, Conservation and Recycling*, 93, 67–74.
<http://doi.org/10.1016/j.resconrec.2014.10.004>

- WRAP and Environmental Resources Management Ltd (ERM). (2008). Technical Report: Life Cycle Assessment of Plasterboard.
- WRAP, & BSI. (2013). PAS 109:2013. Specification for the production of reprocessed gypsum from waste plasterboard. Retrieved 4 May 2016, from [http://www.wrap.org.uk/sites/files/wrap/PAS109 \(2013\).pdf](http://www.wrap.org.uk/sites/files/wrap/PAS109%20(2013).pdf)
- Yuan, H. (2013). Key indicators for assessing the effectiveness of waste management in construction projects. *Ecological Indicators*, 24, 476–484. <http://doi.org/10.1016/j.ecolind.2012.07.022>

6 BEST PRACTICES IN THE END-OF-LIFE STAGE

CHAPTER OVERVIEW

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 cannot be reduced, and therefore the priority should be to appropriately collect and recover EoL products. The aim of this chapter 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.

Submitted to Journal of Cleaner Production⁹

Main research questions addressed and relation

	Research question (and related specific objective in parentheses)	Brief answer and → Relation with other chapters
<div>Chapter 1. Gypsum waste generation and management</div> <div>Chapter 2. Life cycle energy and material flows</div> <div>Chapter 3. Factors influencing post-consumer gypsum recycling</div> <div>PART II: MACRO-LEVEL</div>	What practices adopted by stakeholders affect gypsum waste management? (O6)	Three best practices are considered to be fundamental to enable a circular economy for gypsum products: “Perform on-site segregation of GW” (DE7), “Set clear waste acceptance criteria” (RE4) and “Set clear recycled gypsum quality criteria” (MA1). In addition, 20 best practices are identified for the achievement of an improved deconstruction-recycling value chain. → The proposed best practices affect the EoL stage of gypsum products (performance of this EoL stage can be monitored as detailed in Chapter 5). Moreover, practices influence the quality of RG feedstock (Chapter 4).
<div>Chapter 4. Physical and mechanical characterization</div> <div>Chapter 5. End-of-life case studies analysis</div> <div>Chapter 6. Best practices in the end-of-life stage</div> <div>PART III. MICRO-LEVEL</div>		

⁹ A short version of this Chapter was presented in the Conference “Global Cleaner Production and Sustainable Consumption Conference” in November 2015, in Sitges (Spain). The work was selected for consideration in one of the Special Volumes from the sessions and workshops (to be part of the Journal of Cleaner Production). The Special Volume is entitled “Low carbon economy and equitable society: production, supply chain, and operations management perspectives”.

6.1. Introduction

The destiny 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). EoL construction products (also known as demolition waste) are increasingly generated in the European Union (EU), as the building stock increases and buildings approach the end of their service life (BPIE, 2011). Therefore, building products reach the EoL stage and become EoL products. One report recently estimated a 46% recycling rate of construction and demolition (C&D) waste in the EU (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, as recently studied by 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). 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 “Sect clear waste acceptance criteria” section).

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 & Kahn, 2012; Eleftheriadis & Myklebust, 2015; Farel, Yannou, & Bertoluci, 2013; Kurdve, Shahbazi, Wendin et al., 2014; Mansar & Reijers, 2005; Rose et al., 2015; Rossi, Terzi, & Taisch, 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 & 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.

Previously, the ideal conditions to produce quality RG from EoL gypsum were formulated (Jiménez-Rivero & García-Navarro, 2016). These findings (summarized in Table 6.2) along with a study of the literature and a questionnaire survey, framed this research. This work proposes a set of best practices for the management of EoL gypsum in a circular economy (see Lieder and Rashid (2015) for a recent review on the concept of circular economy). First, a set of 23 good practices were outlined (see “Selected best practices for the management of EoL gypsum in a circular economy” section) and subjected to stakeholder consultation (as described in “Methodology: stakeholder consultation” section). Second, data analysis of the survey results yielded a selection of the fundamental practices at European level.

6.2. 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 project “From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry” (GtoG project, 2013a), which framed this investigation (see Table 6.1). 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 the sub-sections below.

Table 6.1. 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 et al. (2010), Lu and Yuan (2010), Villoria Saez et al. (2013), Antink et al. (2014) and Calvo et al. (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 et al. (2010), Lu and Yuan (2010), Wang et al.(2010), 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 et al. (2010) and Villoria Saez et al. (2013)
DE10	Minimize number of roundtrips to recycling	GtoG project (2015a)
DE11	Perform GW traceability, from source to final destination	Lu, Huang, and Li (2011), Deloitte (2014), Wilson et al. (2014)
RE1	Recycling plant or warehouse strategically located	Beamon and Fernandes (2004), Kourmpanis et al. (2008), Baniyas et al. (2010), Calvo et al. (2014)
RE2	Have an adequate warehouse for GW and RG storage	GtoG project (2015a)
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 (2015a)
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, (2015a)
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 (2015a)
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 (2015a)

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

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 & Caban, 1998; Lu & 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.

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.

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, 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.-a) and the Site Methodology to Audit Reduced Target Waste (SMARTWaste) in the UK.

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).

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 & 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 & Tam, 2002; Tam, 2008). Begum et al. (2009) found that the participation in waste management training programmes cause positive attitudes towards waste management.

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).

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.

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).

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.

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 & García-Navarro, 2016).

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, 2014). This practice can be performed by the worker appointed for the follow-up of the waste management (see DE2).

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) (Bañas et al., 2010).

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/m³ for GW and 0.7 t/m³ for RG (GtoG Project, 2015b).

Operate a quality management system (RE3)

A quality assurance system is an important tool to demonstrate compliance with the RG quality criteria 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, 2012, 2013), 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.

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, 2012, 2013) 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.

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).

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 & Eder, 2011; WRAP & BSI, 2013).

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 & BSI, 2013).

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 & 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, 2015c).

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 & 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 & 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, 2006; WRAP, 2006).

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, 2015b).

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).

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.

Best practices have a positive impact on the recently identified ideal conditions to produce quality RG from EoL gypsum (Jiménez-Rivero & García-Navarro, 2016). The interrelation between these best practices and such most favourable conditions is presented in Table 6.2.

Table 6.2. Best practices and their influence in the ideal conditions to produce quality RG (summarized from Jiménez-Rivero & García-Navarro (2016)).

Influence	Ideal conditions to produce RG from EoL gypsum	Best practice																							
		DE1	DE2	DE3	DE4	DE5	DE6	DE7	DE8	DE9	DE10	DE11	RE1	RE2	RE3	RE4	RE5	RE6	RE7	MA1	MA2	MA3	GE1	GE2	
↓	Deviation GW foreseen - generated	✓	✓	✓	✓	✓	✓	✓	✓	✓														✓	
↓	Impurities in the GW load	✓	✓	✓	✓	✓	✓	✓	✓	✓														✓	
↑	Traceability of the GW	✓	✓		✓							✓								✓		✓			
↑	GW sent to processing	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓								✓	✓	✓	✓	
↓	GW transport emissions	✓			✓			✓		✓	✓		✓												
↓	Recycling route cost				✓								✓												
↑	Quality GW	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓				✓			✓	
↓	Processing and RG transport emissions												✓		✓				✓						
↓	Natural gypsum mined	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓			✓		✓	✓		✓	
↑	Stakeholders' satisfaction	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				✓			✓		✓			✓	
↑	Quality RG	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

6.3. Methodology: stakeholder consultation

A questionnaire (see Appendix 3) was used to investigate stakeholders' views on the selected best practices to successful management (see “Selected best practices for the management of EoL gypsum in a circular economy” section). 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 “Selected best practices for the management of EoL gypsum in a circular economy” section). 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 ($\alpha=0.05$). 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 & 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 & 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 y th score (S_y) for the x th good practice and S_y is the score given by stakeholders for each good practice.

The identification of practices commonly applied in GR but not yet adopted in NGR countries permitted to propose of 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 Section 7.3) in order to be considered a fundamental practice.

6.4. Results and discussion

Table 6.3 summarizes the analysis on the importance given by stakeholders (see "Methodology: stakeholder consultation" section 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 6.3. 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

6.4.1. 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 6.3). 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. 6.1 and Fig. 6.2 provide further insight into this variability in terms of importance, showing that quite different perceptions exist between GR and NGR countries (Fig. 6.1) and stakeholders (Fig. 6.2).

Fig. 6.1. 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. 6.2. Importance given by different stakeholders in GR countries (BE, UK, FR, NL, DK) and NGR countries (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 6.3. 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. 6.1). 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 6.2. “Selected best practices for the management of EoL gypsum in a circular economy”).

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 6.3 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.

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

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

“Set clear waste acceptance criteria” (RE4) was the highest rated practice in terms of importance for an efficient closed-loop supply chain (Table 6.3). 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 A3.1. in Appendix 3 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 ($Z=-4.23$; $p=0.000$).

The second fundamental practice, “Perform on-site segregation of GW” (DE7), ranked second ($M=4.64$; $SD=0.90$) in GR countries (see Table 6.3). This practice is considered to be extremely important by 82% of respondents in GR countries (Fig. 6.1). 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 A3.1. in Appendix 3). 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.

The third identified fundamental practice, “Set RG quality criteria” (MA1), ranked fifth in both group of countries (Table 6.3) and is regarded as extremely important by around 60% of stakeholders in both group of countries (Fig. 6.1). 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, 2015c; WRAP & 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. 6.3. Rate of respondents that highly implement the practice and perceive it as highly feasible, above 4 in the rating scale. Recycling (GR) countries: BE, UK, FR, NL, DK. Non-recycling (NGR) countries: AU, DE, GR, SP, PT.

6.5. 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.

References

- AEA Technology Plc. (2006). Review of Plasterboard Material Flows and Barriers to Greater Use of Recycled Plasterboard.
- Agrela, F., Sanchez De Juan, M., Ayuso, J., Geraldès, V. L., & Jimenez, J. R. (2011). Limiting properties in the characterisation of mixed recycled aggregates for use in the manufacture of concrete. *Construction and Building Materials*, 25(10), 3950–3955. <http://doi.org/10.1016/j.conbuildmat.2011.04.027>
- Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry : Understanding the impediments and requisites for improvements. *Resources, Conservation & Recycling*, 102, 101–112. <http://doi.org/10.1016/j.resconrec.2015.06.001>
- Ali, H. A. E. M., Al-Sulaihi, I. A., & Al-Gahtani, K. S. (2013). Indicators for measuring performance of building construction companies in Kingdom of Saudi Arabia. *Journal of King Saud University - Engineering Sciences*, 25(2), 125–134. <http://doi.org/10.1016/j.jksues.2012.03.002>
- Antink, R., Garrigan, C., Bonetti, M., & Westaway, R. (2014). Greening the Building Supply Chain. UNEP Sustainable Buildings and Climate Initiative. United Nations Environment Programme. Job Number: DTI/1753/PA. Retrieved 17 January 2016, from http://www.unep.org/sbci/pdfs/greening_the_supply_chain_report.pdf
- Audus, I., Charles, P., & Evans, S. (2010). Environmental good practice on site guide (third edition). Construction Industry Research and Information Association (CIRIA).

- Banias, G., Achillas, C., Vlachokostas, C., Moussiopoulos, N., & Tarsenis, S. (2010). Assessing multiple criteria for the optimal location of a construction and demolition waste management facility. *Building and Environment*, 45(10), 2317–2326. <http://doi.org/10.1016/j.buildenv.2010.04.016>
- Barbudo, A., Galvín, A. P., Agrela, F., Ayuso, J., & Jiménez, J. R. (2012). Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes. *Waste Management*, 32(6), 1229–35. <http://doi.org/10.1016/j.wasman.2012.02.005>
- Barczak, G., & Kahn, K. B. (2012). Identifying new product development best practice. *Business Horizons*, 55(3), 293–305. <http://doi.org/10.1016/j.bushor.2012.01.006>
- Beamon, B. M., & Fernandes, C. (2004). Supply-chain network configuration for product recovery. *Production Planning & Control*, 15(3), 270–281. <http://doi.org/10.1080/09537280410001697701>
- Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2009). Attitude and behavioral factors in waste management in the construction industry of Malaysia. *Resources, Conservation and Recycling*, 53(6), 321–328. <http://doi.org/10.1016/j.resconrec.2009.01.005>
- Buildings Performance Institute Europe (BPIE). (2011). Europe's buildings under the microscope.
- Bundesverband der Gipsindustrie e.V. (2013). Recycled gypsum (RC-gypsum). Initial test for recycling plants, quality management, quality requirements and analysis methods. Retrieved 4 May 2016, from http://www.gips.de/wp-content/uploads/downloads/2014/03/Anlage-1a_Gipsrecycling_engl.pdf
- Calvo, N., Varela-Candamio, L., & Novo-Corti, I. (2014). A dynamic model for construction and demolition (C&D) waste management in Spain: Driving policies based on economic incentives and tax penalties. *Sustainability*, 6(1), 416–435. <http://doi.org/10.3390/su6010416>
- Carmines, E. G., & Zeller, R. A. (1979). Reliability and validity assessment. *Quantitative Applications in the Social Sciences*. <http://doi.org/10.1037/018269>
- Chini, A., & Bruening, S. (2003). Deconstruction and materials reuse in the United States. *The Future of Sustainable Construction*, (October), 1–22. Retrieved from <http://www.bcn.ufl.edu/iejc/pindex/109/chini.pdf>
- CIB. (2000). Overview of Deconstruction in Selected Countries (CIB Publication 252). Edited by Charled J.Kibert and Abdol R. Chini. Task Group 39: Deconstruction.
- CIB International Council for Research and Innovation in Building and Construction. (2014). Barriers for Deconstruction and Reuse / Recycling of Construction Materials. (U. S. A. Shiro Nakajima, Building Research Institute, Japan Mark Russell, University of New Mexico, Ed.). CIB Publication 397.
- del Río Merino, M., Izquierdo Gracia, P., & Weis Azevedo, I. S. (2010). Sustainable construction: construction and demolition waste reconsidered. *Waste Management & Research : The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 28(2), 118–129. <http://doi.org/10.1177/0734242X09103841>
- Delgado, L., Sofia-Catarino, A., Eder, P., Litten, D., Luo, Z., & Villanueva, A. (2009). End of waste criteria. Final Report.
- Deloitte. (2014). Screening template for Construction and Demolition Waste management in Belgium.
- Eleftheriadis, R. J., & Myklebust, O. (2015). Benchmark and Best Practice of IFaCOM Industrial Demonstrators. *Procedia CIRP*, 33, 311–314. <http://doi.org/10.1016/j.procir.2015.06.062>
- European Commission (DG ENV). (2011). Service Contract on Management of Construction and Demolition Waste - SR1. Final Report Task 2. A project under the Framework contract ENV.G.4/FRA/2008/0112. Retrieved 17 January 2016, from http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf
- European Committee for Standardization (CEN). EN 15804:2012+A1:2013. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (2013).

- European Parliament and the Council of the European Union. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Retrieved 12 April 2015, from <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:en:PDF>
- Faniran, O. ., & Caban, G. (1998). Minimizing waste on construction project sites. *Engineering, Construction and Architectural Management*, 5(2), 182–188. JOUR. <http://doi.org/10.1108/eb021073>
- Farel, R., Yannou, B., & Bertoluci, G. (2013). Finding best practices for automotive glazing recycling: A network optimization model. *Journal of Cleaner Production*, 52, 446–461. <http://doi.org/10.1016/j.jclepro.2013.02.022>
- Formoso, C. T., M-Asce Soibelman, L., De Cesare, C., & Isatto, E. L. (2002). Material waste in building industry: main causes and prevention. *Journal of Construction Engineering and Management*, 128(4), 316–326. <http://doi.org/10.1061/~ASCE!0733-9364~2002!128:4~316!>
- GtoG project. (2013a). Life+ Gypsum to Gypsum (GtoG) project ‘From production to recycling: a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry’ LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4191
- GtoG project. (2013b). DA1: Inventory of current practices LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from <http://gypsumtogypsum.org/documents/deliverable-a1-report-on-current-practices.pdf>
- GtoG project. (2015a). DA2: Inventory of best practices LIFE11 ENV/BE/001039. Retrieved 17 July 2016, from <http://gypsumtogypsum.org/documents/da2-inventory-of-best-practices.pdf>
- GtoG project. (2015b). DC1. Report on best practice indicators for deconstruction, recycling and reincorporation LIFE11 ENV/BE/001039. Retrieved 17 January 2016, from http://ec.europa.eu/environment/life/news/newsarchive2015/documents/20150715_gtog.pdf
- GtoG project. (2015c). DC2: Protocol of action B2.2: Quality criteria for recycled gypsum, technical and toxicological parameters LIFE11 ENV/BE/001039. Retrieved 13 November 2015, from <http://gypsumtogypsum.org/documents/quality-criteria-for-recycled-gypsum-technical-and-toxicological-parameters.pdf>
- Harpe, S. E. (2015). How to analyze Likert and other rating scale data. *Currents in Pharmacy Teaching and Learning*, 7(6), 836–850. <http://doi.org/10.1016/j.cptl.2015.08.001>
- Heibeler, R., Kelly, T. B., & Ketteman, C. (1998). *Best Practices—Building Your Business with Customer-Focused Solutions*. New York: Simon & Schuster.
- HISER project - H2020 under agreement No. 642085. (n.d.). Demolition case study: business-as-usual in Flanders. HISER Project, News. Retrieved 29 March 2016, from <http://www.hiserproject.eu/index.php/component/content/article?id=117:demolition-case-study-business-as-usual-in-flanders>
- Hjelmar, O., Van Der Sloot, H. a., Comans, R. N. J., & Wahlström, M. (2013). EoW criteria for waste-derived aggregates. *Waste and Biomass Valorization*, 4(4), 809–819. <http://doi.org/10.1007/s12649-013-9261-8>
- Hurley, J. W. (2003). *Valuing the Pre-Demolition Audit Process*. CIB Report 287. Florida, USA.
- Jiménez-Rivero, A., & García-Navarro, J. (2016). Indicators to Measure the Management Performance of End-of-Life Gypsum: From Deconstruction to Production of Recycled Gypsum. *Waste and Biomass Valorization*, 1–15. article. <http://doi.org/10.1007/s12649-016-9561-x>
- Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources, Conservation and Recycling*, 108, 171–181. <http://doi.org/10.1016/j.resconrec.2016.01.014>
- Kourmpanis, B., Papadopoulos, a., Moustakas, K., Stylianou, M., Haralambous, K. J., & Loizidou, M. (2008). Preliminary study for the management of construction and demolition waste. *Waste Management & Research*, 26(3), 267–275. <http://doi.org/10.1177/0734242X07083344>

- Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C., & Wiktorsson, M. (2014). Waste flow mapping to improve sustainability of waste management: a case study approach. *Journal of Cleaner Production*, 98, 304–315. <http://doi.org/10.1016/j.jclepro.2014.06.076>
- Lieder, M., & Rashid, A. (2015). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, 115, 36–51. <http://doi.org/10.1016/j.jclepro.2015.12.042>
- Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. *Waste Management (New York, N.Y.)*, 31(6), 1261–76. <http://doi.org/10.1016/j.wasman.2011.01.023>
- Lönngren, H.-M., Rosenkranz, C., & Kolbe, H. (2010). Aggregated construction supply chains: success factors in implementation of strategic partnerships. *Supply Chain Management: An International Journal*, 15(5), 404–411. <http://doi.org/10.1108/13598541011068297>
- Lu, W., Huang, G. Q., & Li, H. (2011). Scenarios for applying RFID technology in construction project management. *Automation in Construction*, 20(2), 101–106. <http://doi.org/10.1016/j.autcon.2010.09.007>
- Lu, W., & Yuan, H. (2010). Exploring critical success factors for waste management in construction projects of China. *Resources, Conservation and Recycling*, 55(2), 201–208. <http://doi.org/10.1016/j.resconrec.2010.09.010>
- Mansar, S. L., & Reijers, H. a. (2005). Best practices in business process redesign: Validation of a redesign framework. *Computers in Industry*, 56(5), 457–471. <http://doi.org/10.1016/j.compind.2005.01.001>
- Ministerio de la Presidencia. (2008). Real Decreto 105/2008, de 1 de febrero, por el que se regula la producción y gestión de los residuos de construcción y demolición. BOE núm.38.
- Nnorom, I. C., & Osibanjo, O. (2008). Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. *Resources, Conservation and Recycling*, 52(6), 843–858. <http://doi.org/10.1016/j.resconrec.2008.01.004>
- Poon, C. S., Yu, A. T. W., & Ng, L. H. (2001). On-site sorting of construction and demolition waste in Hong Kong. *Resources, Conservation and Recycling*, 32(2), 157–172. [http://doi.org/10.1016/S0921-3449\(01\)00052-0](http://doi.org/10.1016/S0921-3449(01)00052-0)
- Richter, J. L., & Koppejan, R. (2015). Extended producer responsibility for lamps in Nordic countries: best practices and challenges in closing material loops. *Journal of Cleaner Production*, (2015), 1–13. <http://doi.org/10.1016/j.jclepro.2015.06.131>
- Rose, K. a, Sable, S., Deangelis, D. L., Yurek, S., Trexler, J. C., Graf, W., & Reed, D. J. (2015). Proposed best modeling practices for assessing the effects of ecosystem restoration on fish. *Ecological Modelling*, 300, 12–29. <http://doi.org/10.1016/j.ecolmodel.2014.12.020>
- Rossi, M., Terzi, S., & Taisch, M. (2012). Engineering and Design Best Practices in New Product Development : an Empirical Research. *Procedia CIRP*, 21, 2. <http://doi.org/10.1016/j.procir.2014.03.184>
- Shen, L. Y., & Tam, V. W. Y. (2002). Implementation of environmental management in the Hong Kong construction industry. *International Journal of Project Management*, 20(7), 535–543. [http://doi.org/10.1016/S0263-7863\(01\)00054-0](http://doi.org/10.1016/S0263-7863(01)00054-0)
- Silva, R. V., de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, 65, 201–217. <http://doi.org/10.1016/j.conbuildmat.2014.04.117>
- Silvestre, J. D., de Brito, J., & Pinheiro, M. D. (2014). Environmental impacts and benefits of the end-of-life of building materials – calculation rules, results and contribution to a ‘cradle to cradle’ life cycle. *Journal of Cleaner Production*, 66, 37–45. <http://doi.org/10.1016/j.jclepro.2013.10.028>
- Singapore Government. (n.d.-a). Demolition protocol.
- Singapore Government. (n.d.-b). Guidelines for Pre-Demolition Audit, Sequential Demolition and Site Waste Management Plan. Retrieved from https://www.bca.gov.sg/SustainableConstruction/sc_demolition.html

- Szulanski, G. (1996). Exploring Internal Stickiness: Impediments To the Transfer of Best Practice Within the Firm. *Strategic Management Journal*, 17, 27–43.
- Tam, V. W. Y. (2008). On the effectiveness in implementing a waste-management-plan method in construction. *Waste Management*, 28(6), 1072–1080. <http://doi.org/10.1016/j.wasman.2007.04.007>
- Tam, V. W. Y., Fung, I. W. H., Sing, M. C. P., & Ogunlana, S. O. (2014). Best practice of prefabrication implementation in the Hong Kong public and private sectors. *Journal of Cleaner Production*. <http://doi.org/10.1016/j.jclepro.2014.09.045>
- The Council of the European Union. COUNCIL REGULATION (EU) No 333/2011 of 31 March 2011 establishing criteria determining when certain types of scrap metal cease to be waste under Directive 2008/98/EC of the European Parliament and of the Council (2011).
- The European Commission. COMMISSION REGULATION (EU) No 1179/2012 of 10 December 2012 establishing criteria determining when glass cullet ceases to be waste under Directive 2008/98/EC of the European Parliament and of the Council (2012).
- The European Commission. (2013). COMMISSION REGULATION (EU) No 715/2013 of 25 July 2013 establishing criteria determining when copper scrap ceases to be waste under Directive 2008/98/EC of the European Parliament and of the Council, L201/14-L201/20.
- Tovar-Rodríguez, G., Barra, M., Pialarissi, S., Aponte, D., & Vázquez, E. (2013). Expansion of mortars with gypsum contaminated fine recycled aggregates. *Construction and Building Materials*, 38, 1211–1220. <http://doi.org/10.1016/j.conbuildmat.2012.09.059>
- Tukker, A., Groot, H. De, Simons, I., & Wiegiersma, S. (1999). Chemical Recycling of Plastics Waste (PVC and other resins). Delft, the Netherland. TNO-, 7–107. <http://doi.org/STB-99-55> Final
- Villanueva, A., Delgado, L., Luo, Z., Eder, P., Catarino, A. S., & Litten, D. (2010). Study on the selection of waste streams for end-of-waste assessment. Final Report. <http://doi.org/10.2791/41968>
- Villanueva, A., & Eder, P. (2011). End-of-waste criteria for waste paper: Technical proposals. <http://doi.org/10.2791/57814>
- Villoria Saez, P., Del Río Merino, M., San-Antonio González, A., & Porras-Amores, C. (2013). Best practice measures assessment for construction and demolition waste management in building constructions. *Resources, Conservation and Recycling*, 75, 52–62. <http://doi.org/10.1016/j.resconrec.2013.03.009>
- Wang, J., Yuan, H., Kang, X., & Lu, W. (2010). Critical success factors for on-site sorting of construction waste: A china study. *Resources, Conservation and Recycling*, 54(11), 931–936. <http://doi.org/10.1016/j.resconrec.2010.01.012>
- Ward, J. L. (1997). Growing the Family Business: Special Challenges and Practices. *Family Business Review*, 10(4), 323–338. <http://doi.org/10.1111/j.1741-6248.1997.00323.x>
- Wilson, D. C., Rodic, L., Cowing, M. J., Velis, C. A., Whiteman, A. D., Scheinberg, A., ... Oelz, B. (2014). ‘Wasteaware’ benchmark indicators for integrated sustainable waste management in cities. *Waste Management*, 35, 329–342. <http://doi.org/10.1016/j.wasman.2014.10.006>
- WRAP. (2006). Plasterboard Case Study British Gypsum take-back scheme.
- WRAP. (2007). Capture of waste plasterboard on construction sites.
- WRAP. (2011). WRAP Site Waste Management Plan Template version 2.0.
- WRAP, & BSI. (2013). PAS 109:2013. Specification for the production of reprocessed gypsum from waste plasterboard. Retrieved 4 May 2016, from [http://www.wrap.org.uk/sites/files/wrap/PAS109 \(2013\).pdf](http://www.wrap.org.uk/sites/files/wrap/PAS109%20(2013).pdf)
- Zairi, M. (1997). Business process management: a boundaryless approach to modern competitiveness. *Business Process Management Journal*, 3(1), 64–80.
- Zutshi, A., & Creed, A. (2014). An international review of environmental initiatives in the construction sector. *Journal of Cleaner Production*, 98, 92–106. <http://doi.org/10.1016/j.jclepro.2014.06.077>

PART IV: CONCLUSIONS AND FUTURE RESEARCH LINES

GENERAL CONCLUSIONS

This concluding chapter summarizes the findings derived from the study of each specific objective and outlines the limitations of the study. The overall conclusion is that closed-loop gypsum recycling rates are influenced by factors (at a regional, national and EU level) and adopted practices by agents (in each deconstruction-recycling value chain). The lessons learned from current gypsum recycling countries have the potential to enable a circular economy in the rest of the European countries. Detailed conclusions of each chapter of the thesis are included in the corresponding chapters.

Conclusions related to the specific objective O1: Document the current situation on the recycled gypsum market (Chapter 1), divided into O1.1 and O1.2.

O1.1. Document the type and source of gypsum products consumed and gypsum waste recycled.

This study shows that 81% of the gypsum products consumed in the European Union was plasterboard in 2012, according to estimations based on the Eurostat Prodcom database. The rest of the products used were non-faced plaster products, such as gypsum blocks and plaster ceilings. This indicates the type of gypsum product that currently becomes waste during manufacturing and construction processes (however, end-of-life gypsum products currently generated are linked to the type of products consumed decades ago, for which statistics are not available). These gypsum products are well suited to close the material loop of a circular economy. This is due to the chemical composition of gypsum, which enables a changing form based on a reversible hydration reaction (from stucco powder to gypsum products and vice versa). However, gypsum products are currently landfilled in 20 out of the 28 countries. Gypsum recycling countries include France, Benelux (Belgium, the Netherlands, and Luxembourg), Finland, the UK, Denmark, and Sweden.

Two sources of gypsum waste can be distinguished: pre-consumer (from manufacturing processes) and post-consumer (from construction, renovation, deconstruction and demolition works). Pre-consumer gypsum waste is recycled as part of the waste avoidance corporate policy of the manufacturer. All pre-consumer GW is currently assumed to be recycled. The formulation of a life cycle system-wide mass flows enables the estimation of the gypsum waste generated and its final route in 2013. While only 6.4% was sent for closed-loop recycling, 87.2% was landfilled. The rest would have followed other recovery options.

Related limitations:

- The use of gypsum products per country has not been fully assessed for the case of Austria, Belgium, Germany, Poland and the UK, as data is not available for all European countries (Eurostat Prodcom).

- The estimated amount of gypsum waste generated and recovered at EU level is based on assumptions and data from previous studies, as the European database (Eurostat) neither provide data on generation per waste fraction nor detail the waste following the different recovery options.

O1.2. Document the recycled gypsum quality criteria of the European manufacturers.

The recycled gypsum quality criteria in 2012 (i.e. prior to the beginning of the GtoG project) were first explored in Chapter 1. In 2015, initial harmonised voluntary guidelines on quality criteria were produced by the GtoG project, as presented in Table 4.1 and Table 4.4 in Chapter 6. No real consensus on the values currently exists, as the Eurogypsum Recycling Working Group recommends more restrictive values for several of the technical parameters (i.e. free moisture, purity, total organic carbon and water soluble salts).

Related limitations:

- The waste acceptance criteria per country were outlined based on the gypsum recyclers participating in the GtoG project and their area of coverage, as information from other gypsum recyclers could not be gathered.

Conclusions related to the specific objective O2: Evaluate the impact of different levels of gypsum plasterboard recycling and landfilling (Chapter 2)

The relations between gypsum recycling, energy use and GHG emissions have been established. The reincorporation of higher amounts of recycled gypsum content into new plasterboard is evaluated in terms of primary energy use (MJ/m²) and potential contribution to global warming (GHG emissions expressed as kg CO₂eq/m²). To this end, a life cycle model of gypsum plasterboard is developed. Three scenarios are designed: the zero recycling case (0% recycling), the 2013 base case (6.4% closed-loop recycling) and the high recycling case (93.6% closed-loop recycling). Compared to the 2013 base case, primary energy use increases by 1% in the high recycling case (from 43.09 MJ/m² to 43.62 MJ/m²). In terms of kg CO₂eq, a decrease by 9% is achieved (from 2.45 kg CO₂eq/m² to 2.23 kg CO₂eq/m²). Overall, while greater impacts occur in the processes of transport of plasterboard waste to recycling and waste processing, pre-processing stage and transport of recycled gypsum, lower impacts are observed in gypsum mining, transport of natural gypsum and final disposal.

Related limitations:

- Data on methane emissions released from degradation of plasterboard facing paper in landfills is very limited, and therefore the modelling of landfill emissions in the life cycle model is only based on data from studies published during 2007 and 2008.
- The scenario projections of plasterboard recycling in the reference year 2013 are linked to many assumptions in order to evaluate the EU average plasterboard and therefore they are subject to

a degree of uncertainty. A sensitivity analysis was performed in order to show the effect of varying parameters in the primary energy use and GHG emissions over the life cycle.

Conclusions related to the specific objective O3: Analyse the factors influencing gypsum recycling and landfilling (Chapter 3)

A total of 15 factors are identified as critical for gypsum recycling versus landfilling. These fit into policy, economic, social and environmental aspects. Examples include “Landfill ban” (policy-regulatory instrument), “Landfill tax” (policy-economic instrument), “Price of the recycled gypsum” (economic domain), “Availability of natural/FGD gypsum” (environmental domain) and “Awareness of the impacts of gypsum recycling and gypsum landfilling” (social domain). Policy instruments make up the majority of critical factors, which demonstrates the relevant role of governments to strengthen waste legislation, regulatory frameworks and the enforceability of such instruments in line with the circular economy principles. It should be noted that respondents from gypsum-recycling and non-gypsum recycling countries hold different views on the critical factors. Those performing their activity in non-gypsum recycling countries generally underrate the importance of the factors, except those related to economic aspects (e.g. “Other levies and fines”, “Price of the recycled gypsum”). These findings indicate that stakeholders in non-gypsum recycling countries mostly rely on economic aspects to enhance the recovery of gypsum waste. For its part, responses from gypsum-recycling countries show a higher balance between economic, social, and environmental aspects.

Related limitations:

- Quantitative relationships between factors could not be established, as several factors reflect qualitative information (e.g. awareness of the impacts of gypsum landfilling and gypsum recycling, collaboration between stakeholders) and others quantify quantitative information that is not currently available due to confidential issues (e.g. price of the recycled gypsum).

Conclusions related to the specific objective O4: Analyse the characterization of gypsum feedstock and gypsum products with recycled gypsum (Chapter 4)

The recycled gypsum quality criteria guidelines released by the GtoG project were not met by 54% of the recycled gypsum feedstock samples, which indicates that more effective deconstruction processes and recycling procedures are required. Two distinct parameters have been analysed: technical and toxicological parameters.

Technical parameters such as particle size or purity are considered plant specific, as different facilities commonly require particular limit values. For instance, a smaller gypsum particle size is needed in plants operating with FGD gypsum when compared to plants operating with mined gypsum. Results have been discussed against the GtoG guidelines.

Results from the tests on toxicological parameters, which relate to the heavy metal trace elements in the recycled gypsum, were not fully concluding, especially for the case of nickel (4 of the 13 recycled gypsum samples exceeded the limit value), as different laboratories using the same methodology

obtained different results for the case this element. Procedures and testing methods for trace elements should therefore be revised.

Regarding the mechanical characterization of gypsum products, 85% of the samples (i.e. six out of the seven samples) of plasterboard with high recycled content (between 17 and 28%) complied with the relevant European standard (EN 520). One of the samples presented a flexural strength slightly below (548 N) the minimum value required (550 N). All samples complied with the requirements for density, surface water absorption and surface hardness. Minor changes in the process can enhance the flexural strength when required (e.g. feedstock mix).

Related limitations:

- The results from the characterization of the recycled gypsum feedstock could not be linked with the performance of the deconstruction-recycling value chain, as samples were anonymized for confidentiality reasons. As a result, the conclusions of this part are limited (e.g. unknown origin of trace elements) and therefore broader conclusions could not be outlined.

Conclusions related to the specific objective O5. Identify the ideal conditions to produce recycled gypsum from end-of-life gypsum (Chapter 5)

The ideal conditions to produce quality recycled gypsum from end-of-life gypsum are identified through the analysis of the best level of performance of the 17 key performance indicators developed. These ideal conditions are related to two processes: deconstruction and recycling.

Regarding deconstruction processes, these should ensure that gypsum waste complies with the recycler's waste acceptance criteria. It is thus recommended to perform a pre-deconstruction audit (also known as building inventory or pre-deconstruction survey) prior to the beginning of the on-site activities. An effective audit promotes the implementation of a more precise waste management planning and implementation (ideally suited to achieve cost and emissions savings). The deconstruction processes themselves should ensure that the impurities are minimized through segregation of gypsum waste and separate storage on-site. The appointment of skilled workers in waste handling, including the supervision of waste management, contributes to an effective deconstruction. A sound traceability should also be applied, ensuring that waste is conveyed to the most appropriate treatment according to the waste hierarchy.

As regards the recycling processes, these should ensure that recycled gypsum complies with the manufacturer's quality criteria. To this end, an adequate warehouse space and recycling unit should be set up. The quality criteria include technical and toxicological parameters, values that are largely influenced by the deconstruction processes along with the hand-cleaned performed prior to waste processing.

Related limitations:

- The performance indicators were developed considering the available data from five pilot projects, as part of the monitoring protocol for data collection and analysis. The content of the indicators is therefore simpler than desired, which in turn can be considered an added value in terms of usability.
- Certain information, especially those related to economic data, is commonly considered sensitive by stakeholders and therefore detailed economic parameters could not be included in the study.

Conclusions related to the specific objective O6: Analyse practices for the management of end-of-life gypsum in a circular economy (Chapter 6)

A set of best practices for closing the loop of gypsum products in a circular economy are identified. These practices mainly relate to deconstruction and recycling processes. Moreover, stakeholders' views on best practices (per activity and per type of country) are explored. Three best practices are proposed as fundamental to enable gypsum recycling: "Perform on-site segregation of gypsum waste", "Set clear waste acceptance criteria" and "Set clear recycled gypsum quality criteria".

Related limitations:

- Stakeholder's views could not be gathered from all European countries, as responses were only received from five gypsum-recycling countries (Belgium, the United Kingdom, France, the Netherlands and Denmark) and five non-gypsum recycling countries (Austria, Germany, Greece, Spain and Portugal). Nonetheless, these countries are considered representative of gypsum recycling and non-gypsum recycling contexts.
- Stakeholder's views were analysed per type of country (recycling and non-gypsum recycling), as the number of responses did not enable a country-by-country analysis.

FUTURE RESEARCH LINES

The following research lines are identified as a consequence of the results, conclusions and limitations of this thesis.

- Compile the monitoring and reporting mechanisms on C&D waste in the different regions and countries with the aim of creating a detailed and unified European waste flow database (which could be integrated as part of Eurostat), including aspects such as source, fraction, weight, final destination of the waste.
- Perform laboratory experiments or site measurements of methane released from the decomposition of lining paper in different types of landfills and conditions.
- Develop future scenario projections of gypsum recycling, e.g. by 2030 and 2050, based on the life cycle model developed in Chapter 2. That long-term assessment is considered of great importance as regards the quantification of the product, as the amount of end-of-life gypsum is estimated to increase in the next decades, due to the fact that the use of plasterboard in Europe has gained in popularity since the mid-1980s.
- Formulate a model to assess the performance of C&D waste recycling systems. The model could be based on the critical factors identified for the gypsum fraction (Chapter 3), replicated to other waste streams, and the definition of assessment criteria. The model would facilitate the comparison among regions and countries and the analysis of different current and future scenarios.
- Investigate the procedures and testing methods for trace elements, in order to discern the origin of the observed discrepancy between results from distinct laboratories applying the same methodology.
- Replicate the procedure for developing best practice indicators for end-of-life gypsum in other end-of-life products.
- Develop harmonized indicators to measure C&D waste management towards a more circular economy, framed in a common EU monitoring framework.
- Replicate the proposed set of best practices for the management of end-of-life gypsum in other regions and waste fractions.
- Investigate the more adequate European quality criteria for recycled gypsum, per type of manufacturing plant, based on the GtoG guidelines and the Eurogypsum Recycling Working Group recommendations.

PART V: APPENDICES

APPENDIX 1. SUPPLEMENTARY DATA ASSOCIATED WITH THE LIFE CYCLE MODEL

Supplementary Data

Life cycle energy and material flow implications of gypsum plasterboard recycling in the European
Union

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<http://dx.doi.org/10.1016/j.resconrec.2016.01.014>

Table A1.1. Mass flows of raw materials, products and waste in the three different scenarios, in million tonnes per year.

Mass flows	Zero recycling case	2013 base case	High recycling case
Gypsum mining (all uses)	25.39	24.91	23.26
Total gypsum in plasterboard	10.63	10.63	10.63
Natural gypsum	7.61	7.04	5.51
FGD gypsum	3.02	3.02	3.02
Recycled gypsum	0.00	0.56	2.10
Pre-consumer recycled gypsum	0.00	0.45	0.45
Post-consumer recycled gypsum	0.00	0.11	1.65
Paper	0.45	0.45	0.45
Additives	0.15	0.15	0.15
Production waste	0.48	0.48	0.48
Production waste derived RG	0.00	0.45	0.45
Waste paper	0.00	0.05	0.17
Plasterboard	10.73	10.73	10.73
Post-consumer plasterboard waste (total)	1.90	1.90	1.90
To recycling	0.00	0.12	1.77
To landfill	1.77	1.65	0.00
To other uses	0.12	0.12	0.12
Plasterboard waste to landfill	2.26	1.65	0.00

Figure A1.1. Life cycle system-wide mass flows associated with gypsum plasterboard. The numbers indicate million tonnes of material flows in the EU-27 in the reference year 2013 and is the basis of the High recycling case (top) and Zero recycling case (bottom) described in “Scenario projections of plasterboard recycling” of Chapter 3.

Table A1.2. Life cycle inventory data.

Process	Material	Derived from Source	Energy input	Value Unit	MJ/tonne (total)	kg CO ₂ eq/tonne (total)
Gypsum mining	Natural gypsum	Ecoinvent v2.2 (2012)	Various	0.35 MJ/kg	353.85	2.03
FGD gypsum (burdens to get a saleable product)	FGD gypsum	WRAP and ERC (2008)	Coal	1.40 MJ/kg	1,400.00	1.52E-04
Paper	Paper	Ecoinvent v2.2 (2012)	Various	16.45 MJ/kg	16,445.27	986.58
Additives	Additives ^b	Ecoinvent v2.2 (2012)	Various	34.20 MJ/kg	34,200.00	1,208.00
Transport	All materials	EEA (2011) and IEA (2008) ^a	Various - Road	2.73 MJ/tkm	n.a.	n.a.
			Various - Rail	76.00 g CO ₂ eq/tkm	n.a.	n.a.
			Various - Ship	0.63 MJ/tkm	n.a.	n.a.
			Various - Ship	21.00 g CO ₂ eq/tkm	n.a.	n.a.
			Various - Ship	0.47 MJ/tkm	n.a.	n.a.
			Various - Ship	13.00 g CO ₂ eq/tkm	n.a.	n.a.
Plasterboard manufacturing (pre-processing)	Natural gypsum	WRAP and ERC (2008) from Ecoinvent	Grid electricity	4.80 kWh/tonne	80.56	3.76
	FGD gypsum	WRAP and ERC (2008) from Ecoinvent	Natural gas	28.72 MJ/tonne	450.30	29.19
	Recycled gypsum (pre and post-consumer)	WRAP and ERC (2008) from Ecoinvent	Grid electricity	3.80 kWh/tonne	226.47	11.80
			Natural gas	409.26 MJ/tonne		
			Grid electricity	10.00 kWh/tonne		
			Natural gas	118.47 MJ/tonne		
From gypsum mining to total plasterboard manufacturing	Plasterboard	ELCD database 2.0 (2007-2014) (Cradle-to-gate process data set)	Various	35.90 MJ/m ²	3,590.00	195.79
Bulding contruction, Use and EoL: Demolition	Plasterboard	Doka (2003)	Diesel	35.90 MJ/tonne	35.90	3.37
Bulding contruction, Use and EoL: Waste segregation	Plasterboard	WRAP and ERC (2008)	Diesel	30.30 MJ/tonne	30.30	2.84
Waste processing	Pre-consumer plasterboard waste	WRAP and ERC (2008) from Ecoinvent	Grid electricity	9.60 kWh/tonne	150.35	7.99
	Post-consumer plasterboard waste	WRAP and ERC (2008) from Ecoinvent	Diesel	46.67 MJ/tonne	139.23	6.76
Operation of landfill site	Plasterboard waste	Plimmer, Davies, & Carter (2007)	Grid electricity	9.90 kWh/tonne	63.83	5.99
			Diesel	32.31 MJ/tonne		
			Diesel	63.51 MJ/tonne		
			Diesel	0.32 MJ/tonne		
Biogenic emissions from landfill	Plasterboard waste	Plimmer, Davies, & Carter (2007) and EPA (2014)	-	4.48 kg CH ₄ /tonne	-	152.32
			-	0.00 kg CO ₂ /tonne	-	-

^aFor energy demand (MJ): Figure 6.11, IEA (2008), Freight Transport Use, by Mode (Average Germany, France and the UK as representative EU-27, according to Eurogypsum (2010). For GWP (g CO₂): EEA (2011). (for ship, maritime value has been taken) <http://www.eea.europa.eu/data-and-maps/figures/specific-co2->

Table A1.3. Primary energy use in MJ per square meter of plasterboard consumed. Zero: Zero recycling case. Base case: 2013 base case. High: High recycling case.

Stage	Process	Zero	Base case	High
Raw material supply, including processing of secondary material input	Gypsum mining	0.26	0.25	0.19
	FGD gypsum	3.94	3.94	3.94
	Paper	6.82	6.82	6.82
	Additives	4.65	4.65	4.65
	Waste processing (Production waste)	0.00	0.07	0.07
	Total raw material supply	15.67	15.72	15.67
Transport of raw material and secondary material to the manufacturer	Transport natural gypsum	1.22	1.13	0.88
	Transport FGD	0.61	0.61	0.61
	Transport recycled gypsum	0.00	0.00	0.05
	Transport paper	0.23	0.23	0.23
	Transport additives	0.07	0.07	0.07
	Total transport of raw and secondary materials	2.13	2.05	1.85
Manufacture of plasterboard an all upstream processes	Plasterboard manufacturing (Pre-processing)	1.84	1.91	2.12
	Plasterboard manufacturing (Calcination, production)	17.84	17.84	17.84
	Total plasterboard manufacturing	19.67	19.75	19.96
Transport of plasterboard to the building site	Transport of plasterboard to the jobsite	5.18	5.18	5.18
Plasterboard installation and/or deconstruction	Building Construction, Use and EoL	0.06	0.06	0.05
Transport of the post-consumer plasterboard waste to waste processing	Transport of post-consumer PB waste to waste processing	0.00	0.05	0.68
Waste processing of post-consumer plasterboard waste	Waste processing	0.00	0.02	0.23
Final disposal of plasterboard	Transport of post-consumer PB waste to landfill	0.23	0.17	0.00
	Operation of landfill site	0.13	0.10	0.00
	Biogenic emissions from landfill	0.00	0.00	0.00
	Total final disposal	0.36	0.27	0.00
		43.08	43.09	43.62

Table A1.4. Primary energy use in TJ per year within the EU-27 plasterboard life cycle. Zero: Zero recycling case. Base case: 2013 base case. High: High recycling case.

Stage	Process	Zero	Base case	High
Raw material supply, including processing of secondary material input	Gypsum mining	284.05	263.10	205.63
	FGD gypsum	4,229.30	4,229.30	4,229.30
	Paper	7,318.82	7,318.82	7,318.82
	Additives	4,991.09	4,991.09	4,991.09
	Waste processing (Production waste)	0.00	72.63	72.63
	Total raw material supply	16,823.26	16,874.94	16,817.46
Transport of raw material and secondary material to the manufacturer	Transport natural gypsum	1,305.82	1,209.52	945.30
	Transport FGD	659.66	659.66	659.66
	Transport recycled gypsum	0.00	3.83	56.41
	Transport paper	243.29	243.29	243.29
	Transport additives	79.78	79.78	79.78
	Total transport of raw and secondary materials	2,288.54	2,196.08	1,984.44
Manufacture of plasterboard an all upstream processes	Plasterboard manufacturing (Pre-processing)	1,973.05	2,054.89	2,279.44
	Plasterboard manufacturing (Calcination, production, etc)	19,145.64	19,145.64	19,145.64
	Total plasterboard manufacturing	21,118.69	21,200.53	21,425.08
Transport of plasterboard to the building site	Transport of plasterboard to the jobsite	5,564.29	5,564.29	5,564.29
Plasterboard installation and/or deconstruction	Building Construction, Use and EoL	63.72	63.05	53.78
Transport of the post-consumer plasterboard waste to waste processing	Transport of post-consumer PB waste to waste processing	0.00	49.44	727.74
Waste processing of post-consumer plasterboard waste	Waste processing	0.00	16.79	247.13
Final disposal of plasterboard	Transport of post-consumer PB waste to landfill	246.88	180.88	0.00
	Operation of landfill site	144.12	105.59	0.00
	Biogenic emissions from landfill	0.00	0.00	0.00
	Total final disposal	391.00	286.47	0.00
		46,249.51	46,251.60	46,819.93

Table A1.5. GHG emissions in kg CO₂ eq per square meter of plasterboard consumed. Zero: Zero recycling case. Base case: 2013 base case. High: High recycling case.

Stage	Process	Zero	Base case	High
Raw material supply, including processing of secondary material input	Gypsum mining	0.01	0.01	0.01
	FGD gypsum	0.43	0.43	0.43
	Paper	0.41	0.41	0.41
	Additives	0.16	0.16	0.16
	Waste processing (Production waste)	0.00	0.00	0.00
	Total raw material supply	1.02	1.02	1.01
Transport of raw material and secondary material to the manufacturer	Transport natural gypsum	0.03	0.03	0.02
	Transport FGD	0.02	0.02	0.02
	Transport recycled gypsum	0.00	0.00	0.00
	Transport paper	0.01	0.01	0.01
	Transport additives	0.00	0.00	0.00
	Total transport of raw and secondary materials	0.06	0.06	0.05
Manufacture of plasterboard an all upstream processes	Plasterboard manufacturing (Pre-processing)	0.11	0.11	0.12
	Plasterboard manufacturing (Calcination, production)	0.86	0.86	0.86
	Total plasterboard manufacturing	0.96	0.97	0.99
Transport of plasterboard to the building site	Transport of plasterboard to the jobsite	0.14	0.14	0.14
Plasterboard installation and/or deconstruction	Building Construction, Use and EoL	0.01	0.01	0.00
Transport of the post-consumer plasterboard waste to waste processing	Transport of post-consumer PB waste to waste processing	0.00	0.00	0.02
Waste processing of post-consumer plasterboard waste	Waste processing	0.00	0.00	0.01
Final disposal of plasterboard	Transport of post-consumer PB waste to landfill	0.01	0.00	0.00
	Operation of landfill site	0.01	0.01	0.00
	Biogenic emissions from landfill	0.32	0.23	0.00
	Total final disposal	0.34	0.25	0.00
		2.53	2.45	2.23

Table S6. GHG emissions, in kt of CO₂ eq per year, of the EU-27 plasterboard life cycle. Zero: Zero recycling case. Base case: 2013 base case. High: High recycling case.

Stage	Process	Zero	Base case	High
Raw material supply, including processing of secondary material input	Gypsum mining	15.44	14.30	11.18
	FGD gypsum	458.86	458.86	458.86
	Paper	439.07	439.07	439.07
	Additives	176.29	176.29	176.29
	Waste processing (Production waste)	0.00	3.86	3.86
	Total raw material supply	1,089.67	1,092.39	1,089.26
Transport of raw material and secondary material to the manufacturer	Transport natural gypsum	36.37	33.69	26.33
	Transport FGD	18.84	18.84	18.84
	Transport recycled gypsum	0.00	0.11	1.57
	Transport paper	6.76	6.76	6.76
	Transport additives	2.22	2.22	2.22
	Total transport of raw and secondary materials	64.20	61.62	55.72
Manufacture of plasterboard an all upstream processes	Plasterboard manufacturing (Pre-processing)	116.77	121.28	133.66
	Plasterboard manufacturing (Calcination, production)	918.32	921.00	928.36
	Total plasterboard manufacturing	1,035.08	1,042.28	1,062.03
Transport of plasterboard to the building site	Transport of plasterboard to the jobsite	154.71	154.71	154.71
Plasterboard installation and/or deconstruction	Building Construction, Use and EoL	5.98	5.91	5.04
Transport of the post-consumer plasterboard waste to waste processing	Transport of post-consumer PB waste to waste processing	0.00	1.37	20.23
Waste processing of post-consumer plasterboard waste	Waste processing	0.00	0.82	12.00
Final disposal of plasterboard	Transport of post-consumer PB waste to landfill	6.86	5.03	0.00
	Operation of landfill site	13.52	9.90	0.00
	Biogenic emissions from landfill	343.95	252.00	0.00
	Total final disposal	364.33	266.93	0.00
		2,713.96	2,626.04	2,399.01

References used in the Supplementary Data

Doka, G. (2003). Life Cycle Inventories of Waste Treatment Services. ecoinvent report No. 13. Part V. Building Material Disposal. Final report of the project of a National Life Cycle Inventory Database “ecoinvent 2000” commissioned by BUWAL/BFE/ASTRA/BLW. Dübendorf.

Ecoinvent. (2012). Ecoinvent v2.2 Life Cycle Inventory (LCI) database, Gypsum, mineral, at mine/CH S.

European Commission Joint Research Centre - European reference Life-Cycle Database. (2007). Process data set: Gypsum plasterboard (03.00.000). Gypsum plasterboard;technology mix of plasterboard production;production mix at factory;12.5 mm thick, 10kg/m². Retrieved November 9, 2015, from <http://eplca.jrc.ec.europa.eu/ELCD3/showProcess.xhtml;jsessionid=2703835E85D137D1E5882A56E8BBD0C6?uuid=cc39e70e-4a40-42b6-89e3-7305f0b95dc4&version=03.00.000>

International Energy Agency. (2008). Worldwide Trends in Energy Use and Efficiency INDICATORS. Key Insights from IEA Indicator Analysis. IEA Publications.

Plimmer, B., Davies, S., & Carter, L. (2007). Report on Life Cycle Assessment of Plasterboard PBD014, Landfill Emissions Inventory 07514290064.500.

United States Environmental Protection Agency EPA. (2015). Landfilling. Retrieved November 9, 2015, from <http://www3.epa.gov/epawaste/conservation/tools/warm/pdfs/Landfilling.pdf>

WRAP and Environmental Resources Management Ltd (ERM). (2008). WRAP Technical Report: Life Cycle Assessment of Plasterboard.

APPENDIX 2. QUESTIONNAIRE TEMPLATE ON THE FACTORS INFLUENCING GYPSUM RECYCLING

Supplementary Data

Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union

Ana Jiménez-Rivero, Justo García-Navarro

<http://dx.doi.org/10.1016/j.resconrec.2016.09.014>

Questionnaire

Your answers will be anonymous and analysed in combination with other participants, and therefore individual responses will be kept entirely confidential according to the confidentiality clause in the project consortium agreement.

If experiencing any difficulties or needing further information, please get in contact with us:

Research group Sustainability in Construction and Industry

Universidad Politécnica de Madrid (giSCI-UPM)

Contact person: Ana Jiménez Rivero - ana.jimenez@upm.es

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GENERAL DATA	
Which of the following describes your main activity?	Where do you carry out your activity?
Gypsum products designer	
Gypsum products manufacturer	Specify region:
Architect	
Environmental consultant	Experience in the field:
Building project manager	Less than 5 years
Construction company	5-10 years
Deconstruction/demolition company	11-15 years
Waste collector	16-20 years
Gypsum recycler	More than 20 years
Public institution	
Researcher	
Other. Please specify:	

Please rate the following sub-factors regarding their contribution to build a circular economy around gypsum, in terms of :
IMPORTANCE
 Influence of the given sub-factor for successful closed-loop gypsum recycling in the European Union.
 1 - Negligible; 2 - Unimportant; 3 - Neutral; 4 - Important; 5 - Extremely important; N/A - Don't know/Not applicable

FACTORS	IMPORTANCE					
	1	2	3	4	5	N/A
Green Public Procurement criteria impacting C&D waste						
Use of rating systems/building assessment frameworks (e.g. LEED, DGNB, BREEAM)						
Objectives and targets on waste management						
Use of waste management software solutions/waste management tools						
Regulatory framework favouring building selective demolition/deconstruction						
Regulatory framework favouring pre-deconstruction audit						
Regulatory framework favouring Site Waste Management Plan (SWMP)						
Environmental taxes on C&D waste (landfill tax)						
Landfill ban impacting gypsum waste						
Landfill operation cost (e.g. operating monocells, gypsum waste pre-treatment)						
Strategy of the recycler (sources, brands or type of board accepted)						
Recycler's gate fee						
Legal alternative destinations that do not favour the options that are higher in the waste hierarchy						
Change of the legal status from waste to non-waste (secondary material) - End-of-waste status						
Price of the recycled gypsum						
Reduced availability of natural and/or FGD gypsum						
Other levies and fines (e.g. levy on primary raw materials, penalties to limit unauthorized disposal)						
Regulatory framework favouring the use of recycled materials						
Collaboration between the supply chain						
Awareness of the impacts of gypsum landfilling and gypsum recycling						

Comments

Please provide your contact information in case you would agree to be interviewed (phone interviews might be needed in order to deepen in the stakeholders' view)

Composition of the respondents

Fig. A2.1. Break down per country. GR countries (BE, UK, FR, NL, DK) have been represented with a squared pattern.

NGR countries (AU, DE, GR, SP, PT) have been represented with a lined pattern.

Fig. A2.2. Break down per agent. The different fills present the agent or group of agents as considered in the manuscript, i.e. Solid fill, grey: Manufacturers; Lined pattern: construction agents; Dot pattern: waste collectors and gypsum recyclers; No fill: others.

Mean value per agent

Table A2.1 . Policy domain, break down per type of stakeholder and type of country

Factor	CF	All	Const GR	Const NGR	Rec GR	Rec NGR	Manuf GR	Manuf NGR	Others GR	Others NGR
Landfill ban	CF1	4.53	4.50	4.00	4.70	-	4.33	3.33	4.50	4.50
Environmental taxes (landfill tax)	CF2	4.51	4.23	4.60	4.50	-	5.00	3.33	4.67	4.36
Regulatory framework favouring the use of recycled materials	CF9	4.26	4.14	4.00	4.44	-	4.17	4.67	4.33	4.50
Regulatory framework favouring building deconstruction	CF10	4.24	4.07	3.60	4.00	-	4.67	4.33	4.50	4.42
Green Public Procurement criteria	CF12	4.16	4.36	3.40	4.00	-	4.00	3.67	4.00	4.17
Legal alternative destinations that do not favour the options that are higher in the waste hierarchy	CF13	4.20	3.54	3.00	3.22	-	2.83	2.00	2.20	2.91
Other levies and fines	CF14	4.00	4.23	4.20	3.88	-	3.33	3.67	4.33	4.36
Regulatory framework favouring SWMP	CF15	4.00	3.79	3.00	0.24	-	4.00	3.33	4.60	4.09

Const: construction agents; Rec: waste collectors and gypsum recyclers; Manuf: manufacturers; Others (researchers, public institutions and associations). GR: gypsum-recycling country; NGR: non-gypsum recycling country. There are no gypsum recyclers operating in NGR countries.

Table A2.2. Economic, social and environmental domains, break down per type of stakeholder and type of country

Factor	CF	All	Const GR	Const NGR	Rec GR	Rec NGR	Manuf GR	Manuf NGR	Others GR	Others NGR
Price of the recycled gypsum	CF3	4.45	4.36	4.40	4.38	-	4.33	4.67	4.83	4.58
Availability of natural and/or FGD gypsum	CF4	4.39	4.38	3.80	4.38	-	4.17	4.33	4.67	4.09
Awareness of the impacts of gypsum landfilling and gypsum recycling	CF5	4.45	4.43	3.17	4.10	-	4.60	2.33	4.33	3.92
Recycler's gate fee	CF6	4.34	3.77	3.83	4.50	-	4.67	3.33	4.33	4.27
Landfill operation cost	CF7	4.29	4.36	3.80	4.10	-	4.40	3.67	4.40	4.20
Objectives and targets on waste management	CF8	4.26	4.29	3.33	4.22	-	4.00	3.00	4.50	4.17
Collaboration between stakeholders	CF11	4.23	4.00	3.17	4.00	-	4.67	2.67	4.67	3.83

Const: construction agents; Rec: waste collectors and gypsum recyclers; Manuf: manufacturers; Others (researchers, public institutions and associations). GR: gypsum-recycling country; NGR: non-gypsum recycling country. . There are no gypsum recyclers operating in NGR countries.

APPENDIX 3. QUESTIONNAIRE TEMPLATE ON THE SELECTED BEST PRACTICES TO SUCCESSFUL MANAGEMENT

Supplementary Data

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

Ana Jiménez-Rivero, Justo García-Navarro

(doi)

Questionnaire

Your answers will be anonymous and analysed in combination with other participants, and therefore individual responses will be kept entirely confidential according to the confidentiality clause in the project consortium agreement.

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Research group Sustainability in Construction and Industry

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GENERAL DATA	
Which of the following describes your main activity?	Where do you carry out your activity?
Gypsum products designer	Specify region:
Gypsum products manufacturer	
Architect	
Environmental consultant	Experience in the field:
Building project manager	Less than 5 years
Construction company	5-10 years
Deconstruction/demolition company	11-15 years
Waste collector	16-20 years
Gypsum recycler	More than 20 years
Public institution	
Researcher	
Other. Please specify:	

The following practices focus on optimal gypsum waste management and the use of recycled gypsum in new gypsum products. Please rate them regarding their contribution to an efficient closed-loop supply chain, in terms of:

IMPORTANCE

Influence of the given practice on closing the loop of gypsum products.
1 - Negligible; 2 - Unimportant; 3 - Neutral; 4 - Important; 5 - Extremely important;

IMPLEMENTATION

Is it a day-to-day practice?
Current probability of occurrence of the given practice, in your national context. 1 - Never; 2 - Seldom; 3 - Occasionally; 4 - Often; 5 - Always; N/A - Don't know/Not

FEASIBILITY

The extent to which they can be applied or put in practice.
1 - Very low; 2 - Low; 3 - Moderate; 4 - High; 5 - Very high; N/A - Don't know/Not applicable

BEST PRACTICES		IMPORTANCE					IMPLEMENTATION					FEASIBILITY							
		1	2	3	4	5	N/A	1	2	3	4	5	N/A	1	2	3	4	5	N/A
DE1	Plan coordination and review meetings about C&D waste																		
DE2	Appointment of a responsible for the follow-up of the waste management																		
DE3	Implement an effective pre-deconstruction audit for gypsum-based systems																		
DE4	Draft a precise Site waste management plan (SWMP) and implement it																		
DE5	Train workers concerning gypsum products dismantling, as well as sorting and storing of gypsum waste																		
DE6	Appointment of trained workers in gypsum products dismantling, as well as sorting and storing of gypsum waste																		
DE7	Perform an on-site segregation of recyclable (e.g. plasterboard, blocks) gypsum waste																		
DE8	Effective planning of gypsum waste capture systems (from source to on-site storage)																		
DE9	Plan number and size of containers needed																		
DE10	Minimize number of roundtrips (from building site to transfer station/recycling)																		
DE11	Perform gypsum waste traceability, from source to final destination																		
RE1	Recycling plant or warehouse strategically located																		
RE2	Have an adequate warehouse for gypsum waste and recycled gypsum storage																		
RE3	Operate a Quality Management System (QMS)																		
RE4	Set clear Waste Acceptance Criteria (WAC)																		
RE5	Perform effective sorting operations prior to gypsum recycling (i.e. remove impurities)																		
RE6	Prepare a schedule of sampling and test frequencies for each quality criteria parameter																		
RE7	Agree suitable supply contracts between recyclers and manufacturers (quantity and quality)																		
MA1	Agree clear recycled gypsum quality criteria																		
MA2	Promote plasterboard take-back schemes																		
MA3	Set a recycled gypsum reincorporation target																		
GE1	Address the End-of-Waste (EoW) status																		
GE2	Availability of suitable closed-top skips																		

Additional data implementation and feasibility

Table A3.1. Results of the questionnaire survey on the implementation and feasibility of best practices

No.	Implementation									Feasibility							
	GR countries			NGR countries			Mann-Whitney			GR countries			NGR countries			Mann-Whitney	
	M	SD	Mdn	M	SD	Mdn	Z	p		M	SD	Mdn	M	SD	Mdn	Z	p
RE4	4.00	1.11	4.00	2.23	1.42	3.00	-3.29	0.001		4.67	0.48	5.00	3.20	1.21	4.00	-4.23	0.000
DE7	4.17	0.89	4.00	3.06	1.24	3.00	-2.84	0.005		4.64	0.90	5.00	3.13	1.45	4.00	-4.00	0.000
RE5	3.96	0.93	3.00	2.20	1.21	3.00	-3.77	0.000		4.58	0.58	5.00	3.07	1.44	3.00	-3.70	0.000
RE2	3.80	1.01	3.00	2.60	1.45	3.00	-2.43	0.015		4.48	0.51	4.00	3.20	1.37	3.00	-2.99	0.003
MA1	4.21	0.98	3.00	2.71	1.49	2.00	-2.86	0.004		4.48	0.81	5.00	3.47	1.64	4.00	-1.86	0.063
RE1	3.67	1.01	3.00	3.07	1.44	2.00	-1.20	0.231		4.39	0.66	4.00	3.20	1.15	3.00	-3.42	0.001
DE2	3.68	1.09	4.00	3.00	1.15	3.50	-1.83	0.067		4.32	0.57	4.00	3.31	1.35	3.50	-2.61	0.009
DE3	3.13	1.06	4.00	2.67	1.11	3.00	-1.30	0.194		4.25	0.72	4.00	2.75	1.13	3.00	-3.82	0.000
DE5	3.52	1.12	3.00	2.36	1.34	3.00	-2.50	0.012		4.23	0.75	4.00	3.00	1.36	3.00	-2.94	0.003
RE3	3.39	1.08	4.00	2.31	1.35	3.00	-2.49	0.013		4.23	0.92	4.00	2.88	1.41	3.00	-3.13	0.002
DE1	3.64	1.14	3.50	3.06	1.12	2.00	-1.56	0.119		4.21	0.85	4.00	3.31	1.20	3.00	-2.33	0.020
DE11	3.27	1.64	4.00	2.29	1.20	3.50	-1.86	0.063		4.19	1.03	4.00	2.38	1.02	2.50	-4.16	0.000
DE4	3.74	1.10	4.00	3.07	1.33	2.00	-1.43	0.152		4.09	1.06	4.00	3.06	1.39	3.00	-2.36	0.018
DE9	3.89	0.94	4.00	2.50	1.51	2.00	-2.67	0.008		4.05	1.09	4.00	3.29	1.59	3.50	-1.38	0.168
DE10	3.43	1.16	4.00	2.60	1.35	2.00	-1.65	0.099		4.05	0.90	4.00	2.94	1.53	3.00	-2.28	0.022
RE7	3.52	1.34	4.00	2.87	1.36	2.00	-1.41	0.159		4.05	1.05	4.00	3.06	1.29	3.50	-2.36	0.018
MA3	3.12	1.54	4.00	2.20	1.01	2.00	-1.80	0.071		4.00	1.00	4.00	2.79	1.53	2.00	-2.36	0.018
RE6	3.24	1.45	4.00	2.42	1.56	2.00	-1.43	0.154		3.96	0.82	4.00	2.92	1.66	3.00	-1.73	0.083
MA2	3.41	1.62	5.00	3.08	1.26	2.00	-0.86	0.390		3.95	0.95	4.00	3.00	1.41	3.00	-1.96	0.051
DE8	3.41	1.37	4.00	2.81	1.68	3.00	-0.92	0.360		3.95	1.24	4.00	3.06	1.53	3.00	-1.74	0.083
GE1	2.87	1.54	3.00	2.53	1.12	2.00	-0.62	0.533		3.85	1.09	4.00	2.84	1.30	3.00	-2.68	0.007
GE2	3.48	1.34	2.00	2.41	1.28	3.00	-2.53	0.011		3.71	1.20	4.00	2.58	1.22	2.00	-3.00	0.003
DE6	3.24	1.34	4.00	2.07	1.16	2.00	-2.50	0.012		3.41	1.33	4.00	2.75	1.34	3.00	-1.47	0.141

APPENDIX 4. POSTER

A summary of the thesis was presented on Thursday 14th of April 2016 at TU Delft, as part of the research stay in the Resources and Recycling Group. The presentation took place in the Resources and Recycling laboratory, as part of the initiative Netherlands Circular Hotspot (NLCH) launched on January 2016. Further information [here](#).

APPENDIX 5. SHORT MOVIE

A movie on gypsum recycling was filmed in Werkendam, The Netherlands, where a mobile gypsum recycling unit is periodically in operation. The script and the shootings were conducted as part of the stay at TU Delft (01/02/2016-01/05/2016). The movie is part of an on-line recycling course leaded by the Resources and Recycling Group at TU Delft.

Topic/Timing/Shot	Gypsum recycling – Script
Reception/30s/ 1. Ana and behind her the waste being unloaded from the truck	1. End-of-life gypsum is mainly composed of plasterboard, which makes up the majority of the recyclable gypsum waste generated in the European Union. Other recyclable gypsum products include gypsum blocks and plaster ceilings.
Impurities/45s/ 2. Hand sorting operations are recorded. 3. Ana takes metal, plastic, wood and AAC while talking.	2. To be accepted for recycling, gypsum waste should have minimum levels of impurities and moisture, in accordance with the waste acceptance criteria of the recycler. Before being stored, hand sorting of all types of impurities is performed by workers. 3. Impurities include metal, plastic and wood. Other products, such as autoclaved aerated concrete, can be confused with gypsum products, and are not accepted in the gypsum recycling plants.
Warehouse, recycling units/25s/ 4. Each area inside of the warehouse is recorded 5. Ana talks, the recycling unit is behind her	4. Warehouses contain three separate areas: a place where gypsum waste is stored before being recycled, the recycling unit, and a place for the resulting recycled gypsum. 5. Recycling units can be either fixed or mobile. In this warehouse, a mobile unit is in operation. It processes up to 30 tonnes of gypsum waste per hour.
Processing steps/50s/ 6. Front-end loader 7. Hopper 8. Main body and exit of recycled gypsum 9. Exit of paper and metal	6. For handling the waste, a front-end loader is often used. 7. Next, gypsum waste is loaded into the hopper. 8. Inside the unit, several mechanical steps take place. These are based on crushing and sieving operations, which are designed to separate the lining paper from the gypsum and thereby obtain recycled gypsum—the main output of the process. 9. Additionally, a magnet separator removes any possible metal fragments. As a consequence, paper waste and metal are two other outputs of the process. These are commonly sent to other industries for further processing.
Quality criteria/10 s 10. Ana holds recycled gypsum. The pile of recycled gypsum is behind her.	10. Recycled gypsum is periodically tested against the quality criteria parameters agreed upon between the final costumer and the recycler.
Total: 160 s = 2 min 40 s	

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ACKNOWLEDGEMENTS

This research was conducted as part of the pre-doctoral contract awarded by Universidad Politécnica de Madrid, in the field of gypsum waste (“Residuos de base yeso y su incorporación al proceso de fabricación de placa de yeso laminado” Ref. CPGI/006/2013), framed by the Gypsum to Gypsum (GtoG) project. The GtoG project is supported by the European Commission – DG Environment through the Life + programme; under contract number LIFE11 ENV/BE/001039. Three research stays have greatly influenced the approach and analysis of the works. These stays were granted by “DG Educación y Cultura”, “Vicerrectorado de Investigación, Universidad Politécnica de Madrid” and “Consejo Social, Universidad Politécnica de Madrid”. All this support is deeply appreciated.

I would like to thank all the people who contributed to make me grow personally and professionally during this journey. To my doctoral supervisor, for the opportunity of learning from him. To the whole giSCI-UPM team, I recall with gratitude all the discussions and brainstorming sessions. To the participants of the GtoG project and the surveyed stakeholders, for sharing their experience and insights on the value chain. To the researchers and professionals that welcomed me warmly into their home institutions, for the time and generous advice. To the Evaluation Committee of the pre-defence, for the suggestions of improvement that helped me to fine-tune this final document. To my English teachers and trainers. To my family and friends, specially to my personal and life coach.