Chapter 2
Moving Towards a Circular Economy in Solid Waste Management: Concepts and Practices

Maria Isabel Dumlao-Tan and Anthony Halog

> *The paradox of life lies exactly in this: its resources are finite, but it itself is endless. Such a contradictory state of affairs is feasible only because the resources accessible to life can be used over and over again.*
>
> *—I.I. Gitelson, author of the book "Man-made Closed Ecological Systems"*

1 Introduction

Wastes are defined as those materials, substances, objects and products that are no longer of use to the consumer in terms of its original purpose, and are then disposed to the environment, usually as prescribed by the law. Based on a study in 2012, global municipal solid wastes (MSW) are expected to increase to approximately 2.2 billion tonnes per year in 2025 (Hoornweg and Bhada-Tata 2012). Wastewater, on the other hand, is also considered a global problem with many regions experiencing different issues: from water disease-related deaths in Africa and Asia to eutrophication in China and Europe (GEO5 2012). Another waste, for example, emissions of carbon dioxide (CO_2) from anthropogenic sources, is reported to be one of the major causes of increase in the global mean temperature. These temperatures are expected to increase by 1.8–4.0 °C between 1980 and 2100 (IPCC 2007). Aside from being considered as consumers of environmental resources, mankind is also considered as producers or generators of wastes which has put a strain on the environment. When the environment is affected, this poses a question to the finiteness of our resources. This chapter focuses on solid wastes, waste management, and the significance of a Circular Economy (CE) to solid waste management.

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1.1 Past, Current and Emerging Issues Related to Solid Wastes

Traditionally, solid wastes are discarded after use, and disposed to the environment. Treatment of solid wastes eventually evolved from a reactive approach to management of wastes. A similar linear economy model that was conventionally followed by manufacturers and industrial processes is described as the "take-make-dispose" approach. However, the improper disposal of solid wastes results in pollution, and causes diverse and adverse environmental and health effects. Historical cases of these effects include the Black Death in the mid-14th century in Europe, and the Payatas Dumpsite tragedy in 2000 in the Philippines. Our modern world will also have to address current and emerging issues related to solid wastes: the presence of nano-particles and nano-materials, marine debris such as the Great Pacific garbage patch, transboundary movement of hazardous wastes and e-wastes, increasing volumes of end-of-life products, urban mining, integration of the informal sector, and immigration (GEO5 2012). Special waste streams have also become significant such as hazardous wastes, electronic wastes, bio-medical wastes, and radioactive wastes. These events and issues warrant the establishment of appropriate solid waste management practices.

However, the definition of wastes as being unwanted is relative, and has different meaning for different people. One person's waste may be another person's useful material. Or a product such as a mobile phone that is already at the end-of-life for certain users can still be used by another user. These solid wastes can either be a resource or a pollutant, or both. For example, lead found in computer circuit boards can be recycled to recover the lead, or it can contaminate the environment if left untreated. There are local governments and businesses which have started to consider end-of-life products as secondary resources. For example, in recent years, e-wastes have been receiving attention as secondary sources of metals because they contain precious metals (e.g., gold, silver and palladium) and special metals (e.g. indium, selenium, tellurium, tantalum, bismuth and antimony). The concentrations of gold and palladium found in printed circuit boards (PCBs) of personal computers are 250 g/t and 110 g/t, respectively (Hagelüken 2005). In the recycling of mobile phones, 80% of the value of the materials is due to gold, followed by 10% from palladium and 7% from silver (Navazo et al. 2014). Likewise, in the same study by Navazo et al. (2014), an average tonne of used mobile phones represents a potential of 128 kg of copper, 0.347 kg of gold, 0.15 kg of palladium, 3.63 kg of silver, 15 kg of nickel, 6 kg of lead, 1 kg of antimony, and 10 kg of tin as well as other metals. Examples of other solid wastes and their potentially recoverable materials are shown in Table 2.1.

Thus, within the perspective of solid waste management, solid wastes can also be characterised by their pollution potential and resource potential. *Pollution potential* is defined as "an attribute of substances that degrade environmental quality if they are treated in an improper way...", whereas *resource potential* is

Table 2.1 Solid wastes and their potentially recoverable materials

Waste	Recoverable resource
Construction and demolition waste	Metals, wood, glass, plastics, paper and cardboard, stone, mortar, gypsum
E-wastes	Metals
Batteries, superconductors, motors and generators, phosphors in fluorescent lamps	Rare Earth Elements (REE)
Food wastes, food processing wastes	Biogas, soil conditioner, specialty chemicals (i.e., pectin from citrus peel, phenols from grapes, casein from milk by-products), animal feed or fish food
Cooking oils and fats	Biofuel
Clothing wastes	Nutrients, polyester, cellulose
Packaging wastes	Glass, plastic, paper and cardboard

Sources: Bermejo (2014), Ellen MacArthur Foundation (2013) and Schüler et al. (2011)

defined as "an attribute that substances, after they are properly treated, contribute to production by positive marginal productivity..." (Hosoda 2007).

1.2 Integrated and Sustainable Waste Management

In order to primarily eliminate or reduce the negative impacts of solid wastes to air, water and land environments, and to public health, proper solid waste management is needed for its generation, storage, collection, transfer and transport, processing and treatment, and disposal. Conventional solid waste management, especially in developed countries, was based on the use of technology. An integrated approach to solid waste management has been developed to address the need for inter-related management options at different habitat scales, of involvement of all stakeholders (government or non-government, formal or informal, profit or non-profit oriented), and of interactions with other urban systems (wastewater treatment, energy production, food production facilities) (Van de Klundert and Anshutz 1999). Based on the waste management hierarchy, integrated solid waste management also focuses on technological solutions for recycling, composting and energy recovery. In the 1990s, a holistic and comprehensive approach to solid waste management was developed to address sustainability (in terms of environmental, social and economic). Through the 2000s, the concept of integrated sustainable waste management (ISWM) has improved, and is used as a basis for solid waste management in developing countries. The core concept of ISWM is based on three dimensions in waste management: (1) the stakeholders, (2) waste system elements (all the elements of the waste management hierarchy), and (3) sustainability aspects (political, institutional, social, financial, economic and technical). The ISWM framework is represented by the "Two Triangles" (Fig. 2.1) (Wilson et al. 2013).

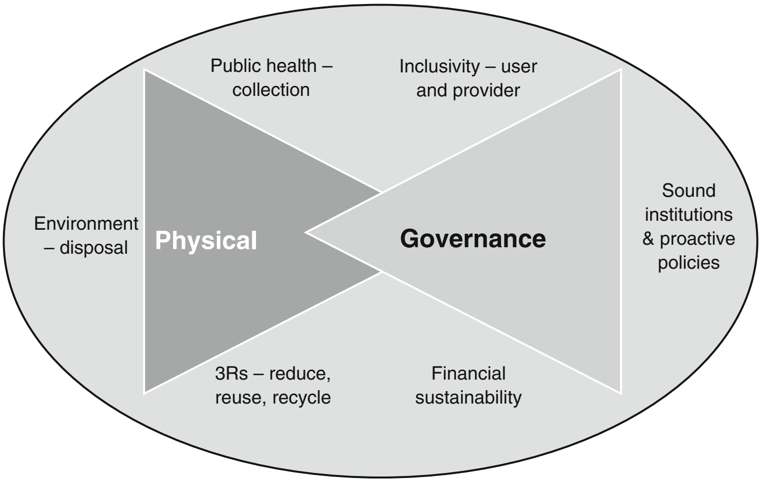


Fig. 2.1 Two triangles of ISWM (©David Wilson, Costas Velis, Ljiljana Rodic; Reproduced with permission)

The first triangle focuses on the three physical (hardware) components:

- Public health: maintaining healthy conditions in cities through a good waste collection service;
- Environment: protection of the environment throughout the waste chain, especially during waste treatment and disposal; and
- 3Rs or resource management: ‘closing the loop’ and returning both materials and nutrients to beneficial use, through preventing waste and striving for high rates of reuse, materials recycling and organics recovery.

The second triangle focuses on the governance (software) components:

- Inclusivity: providing transparent spaces for stakeholders to contribute as users, providers and enablers;
- Financial sustainability: being cost-effective and affordable; and
- A base of sound institutions and pro-active policies.

Looking at the ISWM framework, it has given equal importance to waste minimization, recycling and reuse, together with the other elements (collection, transfer, treatment and disposal). The 3Rs (reduce, reuse and recycle) remain major priorities for a good solid waste management. The 3R philosophy is also the core concept of an integrated resource management. Both ISWM and integrated resource management focus on the direction of implementing the 3Rs based on ‘closing the loop’, eco-design, recyclability of new products, and use of ‘circular economy’ philosophies (Wilson et al. 2013).

2 What Is a Circular Economy?

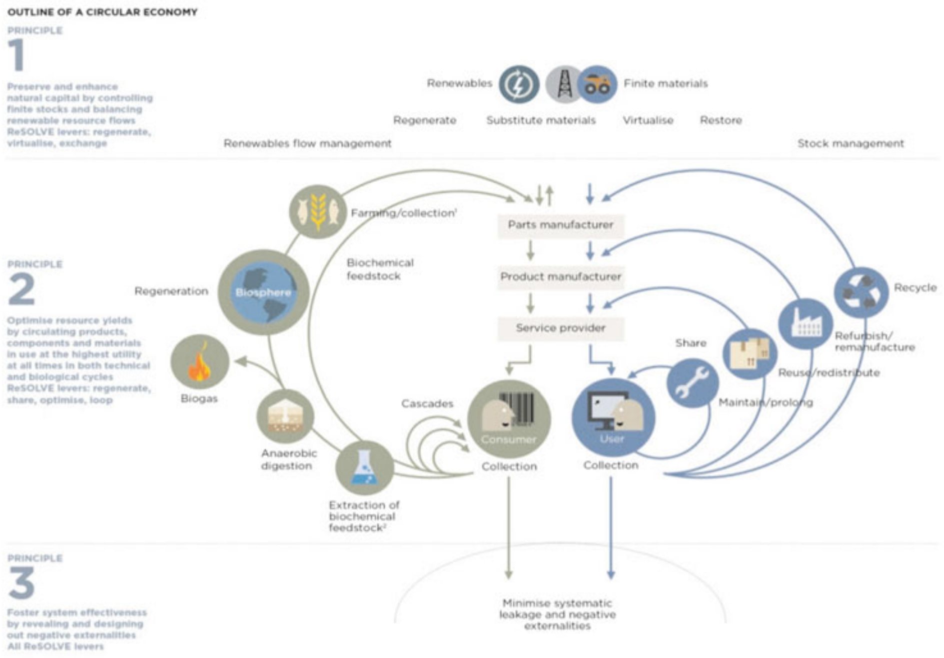
According to the Ellen MacArthur Foundation (EMF), Circular Economy (CE) is defined as “an industrial system that is restorative or regenerative by intention and design; it replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and within this, business models” (Ellen MacArthur Foundation 2016). A generalized illustration summarizes the guiding principle, and the circular loops for renewable and non-renewable materials (Fig. 2.2). The main objectives of the circular economy are to reduce wastage of resources (such as raw materials and energy), to decouple resource consumption from GDP growth, to reduce environmental impacts, and increase human well-being (including increasing employment) (CIRAIG 2015).

The main characteristics of CE can be summarized as: it functions with ‘societies or industries that are imitating the behaviour of ecosystems’; it relies on a closed loop system; it is a paradigm shift from “cradle-to-grave” to “cradle-to-cradle”, from disposability to restorability, from “take-make-dispose” to “take-make-recreate”; it puts more value on use rather than on consumption; promotes materials stewardship; it is focused on eco-effectiveness rather than on eco-efficiency; it is based on systems thinking; and it requires resources which are biodegradable and are possible for permanent reuse (Bermejo 2014; CIRAIG 2015; Florin et al. 2015; Ellen MacArthur Foundation 2016).

2.1 Principles and Scales in a Circular Economy

Principles The EMF illustration of CE is based on the sustainability concept through the recycling of materials, or “nutrients”. Similar to ecological recycling where organic and inorganic matter are circulated in nature through uptake, digestion, release and storage for the production of living matter, the CE nutrients are cycled in specific patterns in a system of inputs and outputs. There are two CE nutrients: (1) biotic nutrients (which follow metabolic pathways of recycling by the biosphere; eventually they are returned to the soil as nutrients); and (2) technical nutrients (which can be infinitely recycled and reused without loss in quality) (CIRAIG 2015).

Scales or Spatial Levels CE can be applied at three spatial levels: (1) the *micro level* – individual enterprises or firms using cleaner production, (2) the *meso level* – also called the inter-enterprise level; the eco-industrial park level involving clustered or chained industries, and responsible supply chain, and (3) the *macro level* – also called the societal level; between production and consumption systems in regions, between industries and urban environment in an “eco-region” or municipality (CIRAIG 2015; Florin et al. 2015).



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

SOURCE: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Fig. 2.2 Circular economy for renewable and non-renewable resources (Reproduced with permission from Ellen MacArthur Foundation 2016)

2.2 Business Models and System Theories for a Circular Economy

With the understanding that CE was initially developed as an economic imperative, there are five circular business models that can be applied at a company level (CIRAIG 2015):

1. The *Circular Supplies Model* is based on the cradle-to-cradle (C2C) concept that operates on a loop of renewable and/or biodegradable resource.
2. The *Resource Recovery Model* is based on the concept of industrial ecology and operates on the principle of converting wastes into inputs through linked product and industrial life cycles.
3. The *Product Life Extension Model* is based on the core principles of functional economy, and operates on the principle of repair, upgrade, remanufacture and remarketing of products for value retention.
4. The *Sharing Platforms Model* is similar to the collaborative consumption or the share economy concepts where high utilization rate of products or services is maximized through efficient sharing, distribution among users.
5. The *Product as a Service Model* is based on the functional economy principle, and operates by transforming consumers into users in a lease or pay-for-use economic arrangement.

The following discussion describes system theories that serve as core concepts of the business models, and their significance to CE. It also includes discussion of how elements of ISWM are integrated into the different system theories.

2.2.1 Cradle-to-Cradle (C2C)

Braungart and McDonough defined Cradle-to-Cradle (C2C) thinking in the 1990s as a nature-inspired, biomimetic design philosophy, or a "design framework that moves beyond the goal of only reducing an organization's negative impacts (eco-efficiency) to provide an engaging vision for (stake-holders) to create a wholly positive footprint on the planet – environmental, social and economic (eco-effectiveness)" (van Dijk et al. 2014). The concept of eco-efficiency versus eco-effectiveness is best illustrated as "doing things right" (eco-efficiency) vs "doing the right thing" (eco-effectiveness). C2C aims for the products to have a positive environmental footprint instead of aiming for a reduction in negative impacts (i.e., reducing waste amounts or converting wastes into useful materials) (CIRAIG 2015; van Dijk et al. 2014). Rather, C2C is a system "powered by renewable energy in which materials flow in safe, regenerative, closed loops" (van Dijk et al. 2014). Thus, the C2C model can be operationalized using the ISWM elements involving the closed-loop system of manufacture, recovery and reuse that should enable a material (such as metals) to maintain its highest value through many product life cycles (Bollinger 2010). The end-of-life products obtain their resource potential through upcycling and "rematerialization" (rather than dematerialization).

2.2.2 Functional Economy

Stahel's definition of Functional or Performance Economy as a new business model with enterprises retaining ownership of long life-span goods combined with lower energy and materials demand for the production phase made possible by appropriate design (CIRAIG 2015). Its concept is also related to the Product Service System (PSS) defined as "a marketable set of products and services and capable of jointly fulfilling a user's need" (CIRAIG 2015). Functional Economy focuses on a looped economy, using waste prevention, refurbishment and reconditioning. Thus, in the context of ISWM, Functional Economy addresses maximization of resource potential of end-of-life products through maintenance, repair and/or remanufacturing of waste into new products resulting in an increase in wealth creation and increase in jobs, whereas it addresses minimization of pollution potential of the end-of-life products through reduction of resources consumption. In relation to CE, their common principle is the longevity and intelligent waste-as-input management (CIRAIG 2015).

2.2.3 Industrial Ecology

Industrial Ecology (IE) is defined as a conceptual framework, an implementation tool; and also called an industrial symbiosis wherein industrial facilities or companies work together in order for one's wastes or by-products to become raw materials for another (CIRAIG 2015). van Dijk et al. (2014) has summarized the principles, elements and strategies for Industrial Ecology in his literature review. To summarize from this review, the main principles of IE are: (i) reduce use or eliminate toxic waste products; (ii) design for environment; (iii) dematerialisation; (iv) substitution of scarce or hazardous materials; (v) repair, reuse, remanufacturing, and (vi) waste mining and (vii) develop more effective technologies to reduce resource consumption.

3 Applications of Circular Economy to Integrated or Sustainable Solid Waste Management

In the case of solid wastes, CE both aims to reduce pollution potential and maximize the resource potential of wastes. Thus, CE is not just a waste management imperative but also a system to link scarce resources and the economy (resource management). Using the functional elements of ISWM, recycling is the most used strategy in a circular economy; however we still need to minimize wastes and reduce the consumption of resources to achieve complete success in a circular economy (Bermejo 2014). One of the initial stages for fully implementing CE is the need for transition in waste management. Figure 2.3 represents the functional elements of ISWM (generation and storage, collection, transfer and transport, treatment and disposal), and the circular loops that can be applied (although not included, the concept should not disregard the significance of the six sustainability aspects: political, institutional, social, environmental, economic and technical; and the stakeholders).

Three categories of solid wastes are explored to demonstrate how CE can be applied to an integrated sustainable solid waste management system: construction and demolition wastes, hazardous wastes, and e-wastes. These categories were selected due to the nature of the resources used, and the wastes generated.

3.1 Gypsum from Construction and Demolition (C&D) Wastes

In developed countries such as European countries, the construction sector contributes significantly to the economy. For instance in EU, it corresponds to about 10% of its GDP. According to EU forecasts, it is predicted that the construction industry will have an annual growth rate of up to 3%. The European Commission has also established the "Construction 2020 Action Plan" in 2013 to ensure that the industry becomes more competitive and experiences sustainable growth. One of the objectives of the said plan is resource efficiency (GtoG report 2015). Construction activities from the construction of buildings and infrastructure to the total or partial demolition, renovation and maintenance of these infrastructures results in the generation of Construction and Demolition (C&D) wastes. C&D wastes are characterized by the presence of numerous materials: concrete, bricks, wood, glass, metal, plastics, solvents, asbestos, gypsum and excavated soil. It can constitute up to 50% of the total solid wastes generated in a country. According to an EU statistical report, in 2008, the construction sector accounted for 32.9% of the total wastes generated in the EU member states (Eurostat 2011). These wastes are considered important to waste management because they represent one of the heaviest and most voluminous waste streams. For resource management, it is of concern because of the increasing demand for raw materials in construction. Another issue to be considered is the presence of toxic substances (i.e., lead, asbestos, solvents) in buildings that could affect the recyclability of the wastes.

Gypsum products include plasterboard, building plaster, drywall, wallboard or sheet rock and gypsum blocks. It was reported in Australia that plasterboard waste in C&D waste stream ranges from 4 to 8%. In the US, a report indicated that drywall accounts for around 13.4% of the C&D waste. Gypsum can be recovered and recycled from these wastes. It is fully and eternally recyclable because its chemical composition does not change (GtoG Report 2015).

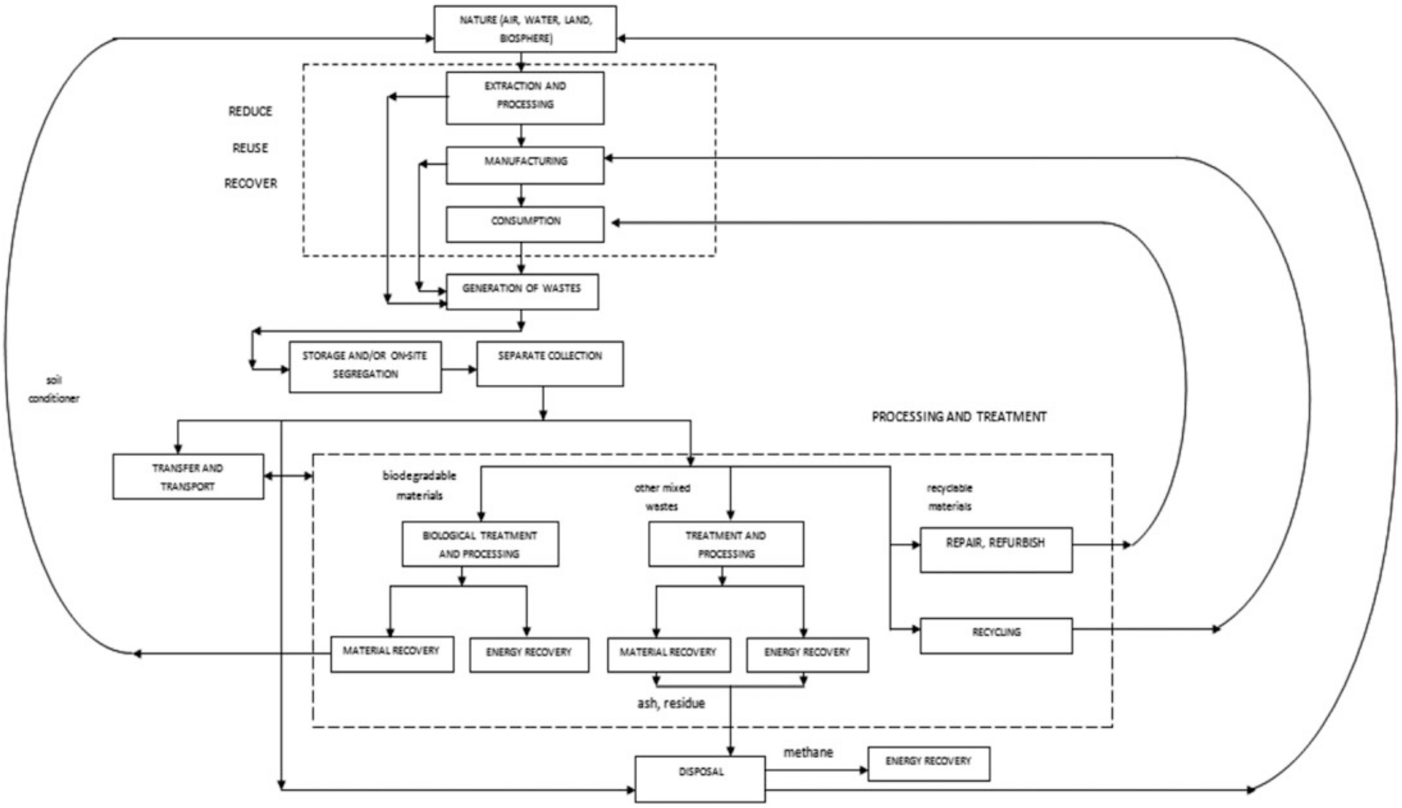


Fig. 2.3 ISWM functional elements and circular loops for circular economy

3.1.1 Which Model Works for This Waste?

A project funded by the European Commission was conducted in 2013–2015. It is called the GtoG project which covers the recycling of plasterboard waste for reintroduction of recycled gypsum into the manufacturing process (GtoG Report 2015). To achieve CE for the Gypsum industry with the demolition and recycling industries, a cradle-to-cradle (C2C) model was applied as shown in Fig. 2.4. The top part of the 'loop' illustrates the manufacture of gypsum products, followed by their use in production. The bottom half of the 'loop' shows how gypsum products can be recycled. It also involves the need for efficient value chain management in which the respective stakeholders participated to extract maximum value of gypsum from plasterboard waste.

- Deconstruction: Plasterboard at the demolition site was dismantled critically, expending effort, time and care. The wastes were separated properly with minimal damage to the waste plasterboard. These activities enable the plasterboard wastes to have high resource potential.
- Reprocessing: Gypsum from plasterboard wastes was recovered and then supplied back to the manufacturing process.
- Reincorporation: The recycled gypsum was used in the process to manufacture new gypsum products.

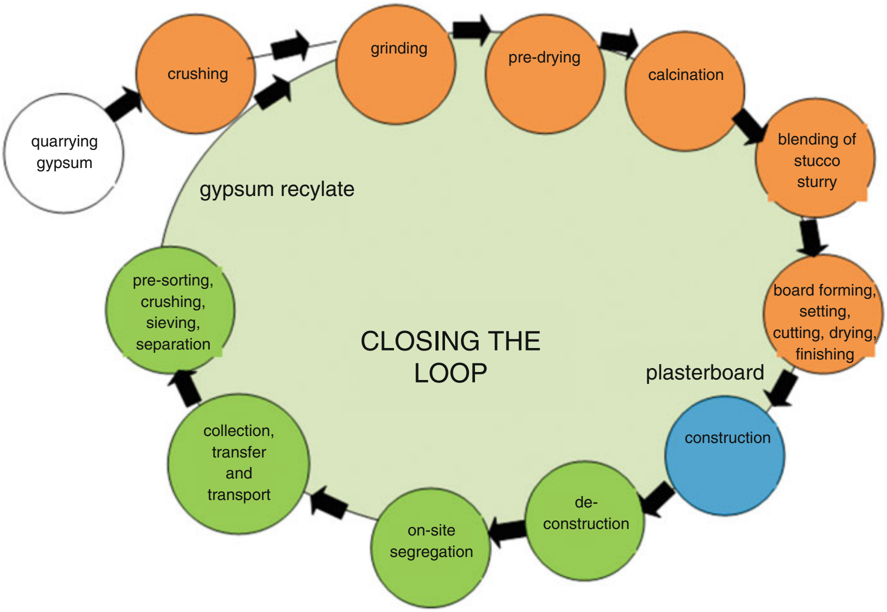


Fig. 2.4 Closing the loop for gypsum from C&D wastes

3.1.2 How Can ISWM Be Applied for a CE Around Gypsum-Based C&D Waste?

An ISWM system for CE around gypsum-based C&D waste begins most importantly with effective dismantling and sorting practices followed by other ISWM functional elements: collection, transfer and transport, and recycling processes.

- On-site segregation: Rather than demolishing construction infrastructure, appropriate techniques and tools are used to dismantle the plasterboard and blocks to minimize the damage to these materials. The gypsum wastes are separated from the other residual C&D waste stream to reduce contamination. The different types of gypsum-based wastes are further sorted (i.e., plaster board, blocks).
- Storage: It is imperative to minimize contamination of gypsum wastes. Thus, containers of specific sizes and quantity are allocated for each type of gypsum-based waste. Closed gypsum steel containers (30 m^3 and 40 m^3 capacity) protect gypsum waste from moisture and wet weather.
- Collection, transfer and transport: Economic and environmental benefits can be achieved by reducing vehicle movement and distances to transport the wastes to a transfer station and/or to a recycling facility.
- Recycling processes: Pre-cleaning and pre-sorting is applied to the wastes prior to the recycling processes. Moisture content is also one of the factors to be considered during recycling, and so the gypsum-based waste is stored with a dryer fraction. The gypsum-based waste undergoes crushing, electromagnetic separation, air separation, and sieving to produce the gypsum recyclate.
- Plasterboard manufacturing: Recycled gypsum is re-introduced during the grinding process and is fed together with the natural gypsum feedstock. Free moisture is removed during the pre-drying process. The feedstock undergoes calcination, which is described as the thermal processing of gypsum to change the hydration state of its dihydrate content by partially or completely removing its chemically bound (or crystal) water in order to produce hemihydrate or anhydrite, respectively. In the manufacture of plasterboards, beta process calcination is used to produce an intermediate product called stucco. The stucco is mixed with water and other dry and liquid additives to produce the slurry for the board's plaster. Board is produced at the forming station, followed by setting and cutting, drying and finishing processes.

3.2 Rare Earth Elements from Phosphorescent Powders in Fluorescent Lamps (FLs)

Linear fluorescent lamps (LFLs) have been in the market for the longest time followed by compact fluorescent lamps (CFLs) and we are now witnessing a transition from fluorescent lights (FLs) to light emitting diodes (LEDs). FLs are considered a concern in municipal solid waste management as they are household hazardous waste which can enter the municipal solid waste (MSW) stream. These FLs contain mercury as vapour inside the glass tubing. Mercury can be released to the environment and bioaccumulate, and it can affect human health causing damage to the nervous system, immune system, reproductive system, motor system, renal system and cardiovascular system. According to the US EPA, a standard FL contains 8–14 mg of mercury, whereas low-mercury bulbs contain 3.5–4 mg of mercury. Data in 2003 reported 620 million FLs disposed in US, which corresponds to a release of approximately 2–4 tons of mercury into their environment (Aucott et al. 2003). In China, waste FLs generated from domestic use alone is predicted to rise to around six billion wastes, or around 937,400 tonnes of waste according to Tan and Li (2014).

Aside from mercury, FLs also contain phosphor powders that are used for their luminescent properties and for producing white light (Machacek et al. 2015). The phosphor powders of FLs contain rare earth elements (REE) such as europium (Eu), terbium (Tb) and yttrium (Y). Thus in the context of resource management, the recovery and recycling of REE from the phosphor powders in FLs presents an option to address resource scarcity of REEs (e.g., global market for REE is increasing by 6% annually) (Solvay 2014). The average composition of FLs, according to the Solvay Loop report is: 88% glass, 5% metals, 4% plastics, 3% powders, and 0.005% mercury. The average composition of the phosphor powders is: 45% halophosphate, 20% glass powder, 20% rare earths, 12% alumina, and 5% others (Solvay 2014). Like other metals, REEs (unlike organic chemicals) are not created or destroyed by biological or chemical processes (although these processes can transform metals from one species, or convert them between inorganic and organic forms), thus in theory metals are eternally recyclable (Reck and Graedel 2012; Schüler et al. 2011; USEPA).

3.2.1 What Model Is Used for This Waste?

Solvay-Rhodia (‘Solvay’) had undertaken a project with EU funding called Solvay “Loop” project which aimed to recycle waste lamp phosphor powders, and to recover REEs. To achieve CE around the recycling of REEs from phosphor powders in waste FLs, Solvay implemented a cradle-to-cradle (C2C) approach, integrating the recycling processes into their existing network (Fig. 2.5). The project focused on the feasibility of using the company’s existing facilities to carry out recycling processes (Solvay 2014).

- Post-consumer waste processing: Solvay already accepts phosphor powders. Thus external recyclers carry the burden of sorting and processing the lamps to produce phosphor powders and a fraction of residual glass.
- Upstream processes (Saint-Fons Chimie plant): Solvay used its own industrial processing facility to separate mercury, glass and other components from the phosphor powders.

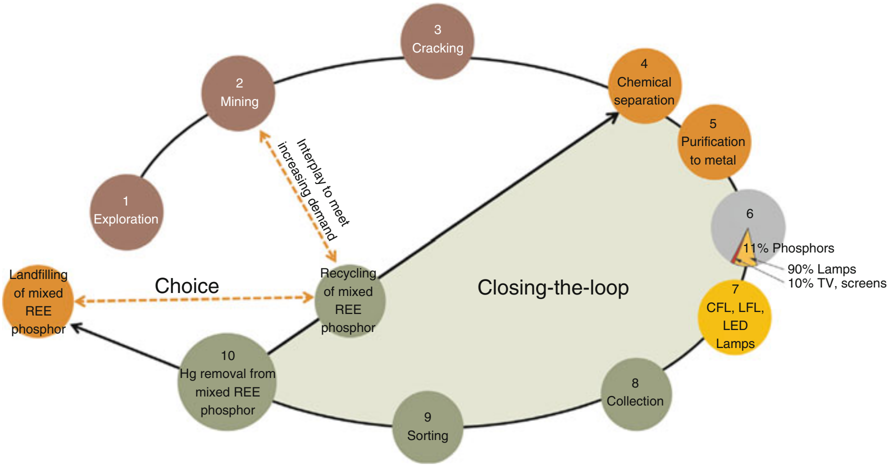


Fig. 2.5 Closing the loop for REEs from phosphor powders in FLs (Reproduced with permission from Machacek et al. 2015)

- Downstream processes (La Rochelle plant): Solvay transported the packaged phosphor powders off-site to one of its other industrial facilities. The processed phosphor powders are purified to recover REEs. The REEs are then reformulated as a supply to manufacture new phosphors.

3.2.2 How Can ISWM Be Applied for CE Around REES from Phosphor Powders in FLs?

To fully achieve CE around the recycling of REEs from the phosphor powders in FLs, the existing network would rely on ISWM for existing separation and purification plants to accept waste phosphor powders. It begins with efficient collection of waste FLs from the consumers. This enables a substantial quantity of waste lamps that can generate secondary resources for REEs. Another important factor to be considered in the post-consumer stage is the dismantling of FLs into different parts; that would enable extraction of maximum value from phosphors.

- Collection: An efficient collection system should enable the consumers to bring the waste FLs, and/or the retailers and manufacturers to accept waste FLs. Examples of collection systems include buy-back programmes and drop-off locations. The wastes are transported to the recyclers of lamps (US EPA 2012).
- Materials recovery: The waste FLs are sorted, dismantled and pre-processed to separate the high-value components from other components such as glass, plastics and metals. Dismantling and pre-processing of the FLs include manual

disassembly, mechanical separation, shredding, screening and demercurization to produce phosphor powders (Solvay 2014; USEPA 2012).

- Recycling processes: Phosphor powders are treated with chemicals in a suspension tank, separated and dried to produce treated powders. The powders then undergo pyrometallurgical thermal treatment, then they are reslurried, filtered, washed and treated with nitric acid. Different REEs are extracted using solvent-extraction processes. Purification of REEs can be done using precipitation, filtration and calcination to produce REE phosphor precursors (Solvay 2014; Machacek et al. 2015).

3.3 Metals from Electronic Wastes (E-Wastes)

Electronic wastes or e-wastes are defined as 'electrically powered appliances that no longer satisfy the current owner for its original purpose' (Singh et al. 2012). The 2006 data estimation by UNEP shows that 20–50 million tons/year of e-wastes is generated globally. MSW contains 1–3% of e-wastes. Global issues regarding the management of e-wastes include (1) increasing volume of obsolescent electronics, (2) increasing rate of generation, (3) decreasing life span of the products, (4) low recycling rate, (5) increasing consumer demand, and (5) illegal transboundary movement of e-wastes from developed to developing countries (Sthiannopkao and Wong 2013; Sepúlveda et al. 2010). Studies conducted in Europe also reported that the quantity of e-wastes is increasing by 3–5% per year (Bhuie et al. 2004). Interestingly, the fastest growing category is cell or mobile phones. In the context of waste management, e-wastes are significant because of their toxic and hazardous substances such as metals, polychlorinated biphenyls (PCBs), brominated fire retardants (BFRs) and plastics, and their impacts. On the other hand, for resource recovery, e-wastes also contain recoverable materials such as plastics, heavy metals, precious metals and rare earth elements. Among the precious metals (PMs) that can be recovered are Au, Ag, Pd, as well as the Base Metals (BMs) like Cu, Pb and Zn. For example, the amount of gold that can be potentially extracted from 1 ton of PCs is reported to be more than that of 17 tons of gold ore. Or for mobile phones, an average tonne of used mobile phones represents a potential of 128 kg of copper, 0.347 kg of gold, 0.15 kg of palladium, 3.63 kg of silver, 15 kg of nickel, 6 kg of lead, 1 kg of antimony, and 10 kg of tin as well as other metals (Navazo et al. 2014). Current e-waste management problems focus on the international trade of e-wastes between developed and developing countries practiced nowadays because valuable materials and substances (copper), rare (yttrium, cerium, lanthanum, europium, terbium, dysprosium, lutetium, gadolinium) and precious (gold, silver, platinum) metals can be sourced from these e-wastes. "Urban mining" (Habuer and Moriguchi 2014) has become another driving force for this trade. E-wastes become secondary sources of these valuable materials (Lundgren 2012) from which the "recyclers" can gain financial benefits.

3.3.1 What Model Can Be Used for E-Waste Management?

Wang et al. (2012) and Manhart (2011) introduced a novel philosophy to address e-waste management issues called the Best-of-Two-Worlds (Bo2W). This concept came from the StEP Initiative (Solving the E-waste Problem) and the United Nations University. It uses the technological and logistic strengths of both developed and developing countries to form a complete recycling chain in the best geographically distributed treatment options in the international or regional arena. Pilot projects were implemented in China and India. Recent Bo2W projects were implemented in Egypt and Ghana. A project by Oeko-Institut in 2012–2015 studied the implementation of Bo2W in two cases: dismantling in Egypt/Ghana and state-of-the-art treatment in European refining plants (Buchert et al. 2016).

- Local pre-processing: Developing countries can still use manual dismantling of the locally-generated e-wastes with low technical requirements. Labour costs in developing countries are also lesser than in industrialized countries (Wang et al. 2012).
- Regional processing: More advanced and automated materials recovery or processing facility can be made available at a regional level.
- End-processing: Industrialized countries offer state-of-the-art and capital-intensive technologies for the overall detoxification and recovery of the valuable materials such as metals (Wang et al. 2012).

3.3.2 How Can ISWM Be Applied to the Bo2W Concept?

The Bo2W approach requires implementation of various elements of ISWM at various geographic locations from a local scale to the global scale.

- Collection: Theoretically, in an efficient collection system, even in developing countries there is need for circularity in e-waste management. Various collection methods can be undertaken by multiple stakeholders: companies, small and medium enterprises (SMEs), public sector, non-government organizations, and the informal sector. Better options can be implemented by retailers and manufacturers using take-back policies or drop-off points. The collection system must ensure that maximum volumes of e-wastes can be brought for recycling.
- Materials recovery: After collection, e-wastes are sorted where useable parts may be used for repair, refurbishment. The wastes are also sorted according to the different types.
- Pre-processing: E-wastes are manually dismantled at local facilities. Automated pre-processing may also be applied to e-waste components using mechanical separation technologies such as screening, magnetic separation, eddy current separation and density separation.
- Recycling processes: E-waste components that require removal of toxic substances are exported to recycling facilities in developed countries. Likewise, the extraction and purification of metals from the pre-processed e-waste components

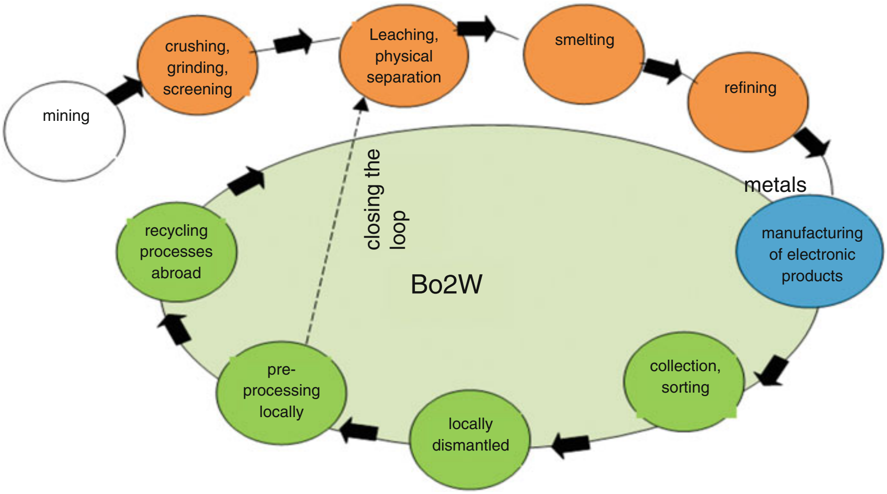


Fig. 2.6 Bo2W and closing the loop model of metals from e-wastes

are done in industrialized countries using various metallurgical processes. Also, recycling processes are based on traditional hydrometallurgical methods of metal extraction from primary ores (Khaliq et al. 2014).

3.3.3 Will a Closed Loop Be Possible for Metals from E-Wastes?

In Australia, the objective of a project called Wealth from Waste Cluster (a three-year project from 2009 to 2012) is to determine the feasibility of metal recovery from discarded products, using expertise in mining and metal extraction processes. Using the conceptual framework for metal flows presented by Golev and Corder (2014) as a basis, the Bo2W model can be improved to integrate the closed loop model as shown in Fig. 2.6. This closed loop is proposed to recycle and recover metals from end-of-life products using processes from the mining and metals manufacturing industry.

4 Summary

From the different examples discussed in this chapter, the following ISWM functional elements contribute to successful implementation of a CE (excluding disposal, which is considered as the last option in the waste management hierarchy):

- Generation of solid wastes: Programmes and strategies to reduce the quantity of solid wastes generated and improve its quality focus on the implementation of

3Rs (reduce-reuse-recycle) such as designing for the environment (green design), material substitution, online retailing. The technical materials could also focus on using resources that can be infinitely recycled.

- On-site segregation and storage: Separation of solid wastes at the source to optimize the quantity and quality of valuable secondary resources. Care, effort, and sometimes skills are required to minimize contamination and deterioration of the useful fractions of solid wastes.
- Collection: Efficient collection systems need to address several factors such as availability, and convenience in order to maximize the capture rate of solid wastes. Current practices include take-back programmes, and drop-off centres. In developing countries, integration of the informal sector optimizes the collection system. Programmes and strategies for efficient collection systems rely increasingly on social and government factors (i.e., public awareness, laws and regulations). In CE, on-site segregation and collection are considered the critical functional elements because they affect the quality and quantity of the secondary resources obtained from the wastes.
- Transfer and transport: Routes between collection centres and materials treatment facilities can be optimized to minimize the distance travelled between facilities. Warehouses or transfer stations may be located in regions where solid wastes generated or purchased are high, or near the recycling facilities. An emerging strategy is to combine the transfer of wastes and recycling processes in a mobile unit.
- Treatment, processing and recovery: In CE, extraction of secondary resources involves pre-processing and end-processing stages. Recycling processes may be complex and extensive, and may require state-of-the-art technologies. When secondary materials are mixed with primary materials during remanufacturing, it may require process and equipment modifications.

References

Aucott, Michael, Michael McLinden and Michael Winka, 2003. Release of mercury from broken fluorescent bulbs. *Journal of the Air & Waste Management Association*, **53**(**2**), 143.

Bermejo, Roberto, 2014. Handbook for a Sustainable Economy. Springer.

Bhuie, A.K., Ogunseitan, O.A., Saphores, J.-D.M. and Shapiro, A.A., 2004. Environmental and economic trade-offs in consumer electronic products recycling: A case study of cell phones and computers. IEEE International Symposium on Electronics and the Environment, 2004. Conference Record.

Bollinger, L.A., 2010. Growing cradle-to-cradle metal flow systems: An application of agent-based modelling and system dynamics to the study of global flows of metals in mobile phones. A thesis paper. Delft University of Technology, Leiden University.

Buchert M, Manhart A, Mehlhart G, Degreif S, Bleher D, Schleicher T, Meskers C, Picard M, Weber F, Walgenbach S, Kummer T, Blank R, Allam H, Meinel J, Ahiayibor V (2016) Transition to sound recycling of e-waste and car waste in developing countries - Lessons learned from implementing the Best-of-two-Worlds concept in Ghana amd Egypt. A synthesis report of the project Global Circular Economy of Strategic Metals - Best-of-two-Worlds approach (Bo2W). Oko-Institute. V., Darmstadt. http://www.resourcefever.org/publications/reports/Bo2W_Synthesis_report_20160323_en.pdf.

CIRAIG International Reference Centre for the Life Cycle of Products, Processes and Services. 2015. Circular Economy: A critical review of concepts. http://www.ciraig.org/pdf/CIRAIG_Circular_Economy_Literature_Review_Oct2015.pdf

Ellen MacArthur Foundation, 2012, 2013. Towards the Circular Economy: Opportunities for the Consumer Goods Sector. Vol. 1&2.

Ellen MacArthur Foundation, 2016. Circular Economy – UK, Europe, Asia, South America & USA. Ellen MacArthur Foundation. http://www.ellenmacarthurfoundation.org/circular-economy

Eurostat, 2011. Waste Statistics. *In:* Archive: Waste Statistics – Statistics Explained. http://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Waste_statistics

Florin, N., Madden, B., Sharpe, S., Benn, S., Agarwal, R., Perey, R. and Giurco, D., 2015. Shifting Business Models for a Circular Economy: Metals Management for Multi-Product-Use Cycles. UTS, Sydney.

GEO5 (Global Environmental Outlook 5), 2012. Global Environmental Outlook 5 – Environment for the future we want. ISBN: 978-92-807-3177-4. United Nations Environment Program, Nairobi.

Golev, A. and Corder, G.D., 2014. Global systems for industrial ecology and recycling of metals in Australia: Research report. Prepared for Wealth from Waste Cluster, by the Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland. Brisbane, Australia - ONLINE.

GtoG, 2015. Gypsum to Gypsum: From Production to Recycling, a Circular Economy for the European Gypsum Industry with the Demolition and Recycling Industry. LIFE11 ENV/BE/001039. <http://gypsumtogypsum.org/>

Habuer, Nakatani J. and Moriguchi, Y., 2014. Time-Series Product and Substance Flow Analyses of End-Of-Life Electrical and Electronic Equipment in China. *Waste Manag*., **34(2)**, 489–497. Elsevier Ltd.

Hagelüken, C., (2006). Improving metal returns and eco-efficiency in electronic recycling—a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining. In: Proceedings of the 2006 IEEE international symposium on electronics and the environment, San Francisco, California, 8–11 May 2006. IEEE, pp 218–223.

Hoornweg, Daniel and Perinaz Bhada-Tata, 2012. What a Waste: A Global Review of Solid Waste Management. World Bank. https://openknowledge.worldbank.org/handle/10986/17388.

Hosoda, Eiji, 2007. International aspects of recycling of electrical and electronic equipment: Material circulation in the East Asian region. *Journal of Material Cycles and Waste Management*, **9(2)**, 140–150.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Khaliq, Abdul, Muhammad Akbar Rhamdhani, Geoffrey Brooks and Syed Masood, 2014. Metal extraction processes for electronic waste and existing industrial routes: A review and Australian perspective. Vol. 3. Basel: MDPI AG.

Lundgren, K., 2012. The Global Impact of E-Waste: Addressing the Challenge. International Labour Office, Programme on Safety and Health at Work and the Environment (Safe Work), Sectoral Activities Department (SECTOR). ILO, Geneva.

Machacek, Erika, Jessika Luth Richter, Komal Habib and Polina Klossek, 2015. Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties. *Resources, Conservation and Recycling*, **104**, 76–93. Doi: 10.1016/j.resconrec.2015.09.005.

Manhart, Andreas, 2011. International cooperation for metal recycling from waste electrical and electronic equipment. *Journal of Industrial Ecology*, **15(1)**, 13–30.

Navazo, V., Manuel, J., Villalba Méndez, G. and Talens Peiró, L., 2014. Material flow analysis and energy requirements of mobile phone material recovery processes. *The International Journal of Life Cycle Assessment*, **19(3)**, 567–579.

Quanyin Tan and Jinhui Li, 2014. A study of waste fluorescent lamp generation in mainland China. *Journal of Cleaner Production*, **81**, 227–233. http://dx.doi.org/10.1016/j.jclepro.2014.06.048.

Reck, B.K. and Graedel, T.E., 2012. Challenges in Metal Recycling. *Science*, **337(6095)**, 690–695. doi:10.1126/science.1217501.

Schüler, D., Buchert, M., Liu, R., Dittrich, S. and Merz, C., 2011. *Study on rare earths and their recycling*. Öko-Institut e.V., Darmstadt.

Sepúlveda, A. et al., 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipment during recycling: Examples from China and India. *Environmental Impact Assessment Review*, **30(1)**, 28–41.

Suthipong Sthiannopkao, Ming Hung Wong, 2013. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Science of The Total Environment, Volumes 463–464, https://doi.org/10.1016/j.scitotenv.2012.06.088.

Singh, R.K., Murty, H.R., Gupta, S.K. and Dikshit, A.K., 2012. An overview of sustainability assessment methodologies. *Ecological Indicators*, **9**(**2**), 281–299.

Solvay, 2014. Loop Life Project, https://www.solvay.com/en/innovation/european-life-projects/loop-life-project-objectives.html, last accessed on 02.03.2016.

U.S. Environmental Protection Agency, 2012. Rare Earth Elements: A review of production, processing, recycling, and associated environmental issues. EPA 2012, 600/R-12/572.

Van de Klundert, A. and Anshutz, J., 1999. Integrated Sustainable Waste Management: The selection of appropriate technologies and the design of sustainable systems is not (only). A technical issue Paper prepared for the CEDARE/IETC Inter-Regional Workshop on Technologies for Sustainable Waste Management, held 13-15 July 1999 in Alexandria, Egypt.

van Dijk, S., Tenpierik, M. and van den Dobbelsteen, A., 2014. Continuing the building's cycles: A literature review and analysis of current systems theories in comparison with the theory of Cradle-to-Cradle. *Resources, Conservation and Recycling*, **82**, 21–34.

Wang, Feng, Jaco Huisman, Christina E. M. Meskers, Mathias Schluep, Ab Stevels, and Christian Hagelüken, 2012. The best-of-2-worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. *Waste management*, **32**(**11**): 2134.

Wilson, D., Velis, C. and Rodic, L., 2013. Integrated sustainable waste management in developing countries. *Waste and Resource Management*, **166(2)**, 52–68.