Environmental Impact and Life Cycle Evaluation of Materials

18

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Abstract

This chapter begins with the presentation of the factors responsible for the sustainability of the construction industry, as it should try optimising its production cycle whilst taking into account materials such as energy and keeping them within thermodynamic limits. Furthermore, the treatment of C&DW is discussed, considering that waste produced should always be reused and/or recycled whenever possible and that which cannot be reused should be sent to landfill, without posing threat to the environment. Another important aspect herein considered is that the construction industry has a positive impact as a large recycling industry of waste and by-products produced in other areas of industry, transforming them and using them in the production of alternative construction materials. Subsequently, detailed information is afforded concerning the interest in the life cycle analysis of this sector increased with the publication of legislation on environmental control, including integrated pollution control and better production techniques.

Keywords

Construction industry • Construction and demolition wastes (C&DW) • Environmental impact • Sustainability • LCA • Recovery of C&DW • Characterisation • Recycled materials • Ecotoxicological effects

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Abbreviations

APA	Portuguese Environment Agency
CFC	Chlorofluorocarbons
C&DW	Construction and demolition waste
ELW	European List of Waste
EPA	Environmental Protection Agency (USA)
EU	European Union
GDP	Gross domestic product
LCA	Life cycle analysis
LNEC	Portuguese National Laboratory of Civil Engineering
MS	Member States of the European Union
MSW	Municipal solid waste
OWM	Organised waste market
SILOGR	Portuguese Information System for Waste Management

18.1 Introduction

The construction industry is one of the main and oldest activities that has aided the economic and social development of nations, thanks to its big impact on the economy, generating capital and creating many jobs.

This sector is not an environmentally friendly one by nature. It uses space that previously belonged to nature and is responsible for consuming large quantities of our planet's natural and energy resources, used to produce the wide range of materials that it incorporates, having a considerable impact on the environment.

It creates pollution through CO_2 emissions and is the third biggest source of emissions in the industrial sector not only on a global level but also within the European Union (EU) [1]. It is responsible for producing waste that contaminates the soil, visual pollution as well as waterline pollution, blocking city drains, which clog or silt up water courses, making them susceptible to flooding; it spreads disease-transmitting agents and also attracts other types of waste, etc. Some of these problems, despite being easy to detect because they can lead to the degradation of urban areas and the quality of life of communities, are very difficult to quantify.

However, construction work can, from an environmental and economic perspective, have a positive impact as a large recycling industry, not only with waste produced by construction itself but also with waste and by-products produced in other areas of industry, transforming them and using them in the production of alternative construction materials. Using these materials should be one of the approaches adopted to reduce the environmental impact of the construction industry's production chain, mainly in terms of consumption of natural resources.

The growing awareness of environmental problems has put pressure on the sustainable development of this industry, by using a more rational construction methodology and with a better management of architectural heritage. The construction industry currently faces the challenge of conciliating its production with the conditions required for the sustainable development that are less harsh on the environment.

The sustainability of the construction industry is a very important issue, as it should try to optimise its production cycle whilst taking into account materials such as energy and keeping them within thermodynamic limits. The waste produced should always be reused and/or recycled whenever possible, and that which cannot be reused should be sent to landfills, without posing a threat to the environment.

The ISO 14001 standards on environmental management provide the construction industry with the elements required. These can be integrated with other management requirements with the aim of achieving both environmental and economic objectives.

18.2 The Construction Industry

18.2.1 The Environmental Impact of the Construction Industry

Construction is an activity that exists in all parts of the world that are occupied by man, from cities to the countryside and even amongst forest dwellers.

Generally speaking, the environmental impact of the construction industry is proportional to its social obligation. Population growth, along with the development of industrial activity, enabled improved living conditions and led to increased demand for homes and building better infrastructure.

Both the positive and negative impacts should be considered whilst trying to balance environmental concerns with the construction industry. As well as the negative impact of destroying the landscape's flora and fauna, there are also other very important effects to consider, caused by the consumption of natural resources (raw materials extraction), energy and pollution. However, by incorporating waste from its own activities or by using waste/by-products from other industries in the production of materials/products or infrastructure, the construction industry has a positive impact on the global supply chain, not only reducing consumption of raw materials but also energy [2, 3].

18.2.1.1 Natural Resources

The consumption of natural resources used as a source of raw material for the production of materials/products applied in this sector is proportional to economic and population growth.

The cost of raw materials has started drastically increasing, due to the growth in the global economy, the expansion of foreign markets, as well as an increase in political instability and regional wars [4, 5].

The amount of natural raw materials consumed by the construction industry not only corresponds to their use in producing construction materials, but also to waste resulting from production processes.

Of all natural resources consumed by the population, around 20–50 % are used by the construction sector. With wood for example, an estimated 26–50 % of wood extracted globally is used as a construction material. In spite of being one of the few resources that is renewable, the problem lies in the unsustainable way in which it is extracted.

Based on the current rate, it is estimated that known reserves of some traditional raw materials, such as for example, iron, copper and zinc, will last 79, 31 and 17 years, respectively, and will soon run out [6].

Intensive exploitation of inert products, in particular sand and natural aggregates, from the reserves located around big cities, has led to their depletion, meaning quarries are being increasingly driven further away from cities. This has meant that raw materials have to be transported further, increasing fuel consumption (energy), and therefore their cost, causing also more pollution. On the other hand, increasing environmental control of the extraction of raw materials and the need to make better use of the land surrounding the most populated areas has led to price rises [3].

The consumption of natural resources to produce the materials/products used in the different stages in the life cycle of the construction industry (building, use, etc.) is considerable, with the majority of this corresponding to the building stage. This consumption, in addition to having a geographical impact, depends on the following factors: (a) the amount of waste produced; (b) waste used for the buildings; (c) technology used; (d) maintenance requirements, including any repairs needed to correct any flaws; and (e) useful lifetime.

The use of materials produced using natural resources in the construction industry should be kept to a minimum by incorporating recycled products, thereby reducing the impact on the environment. The amount of recycled material used should be increased, without forgetting that the new materials produced using waste should meet the necessary requirements that apply for its function and should not be of inferior quality compared to materials produced from natural resources.

18.2.1.2 Energy

In industrialised countries, 40 % of energy consumption is used by the construction industry. This figure includes consumption during the construction stage, use of the building including energy for lighting and air conditioning, and the demolition phase [7, 8].

Using waste to produce materials can also reduce energy consumption, as the distance for transporting secondary raw materials is shorter compared to the distance to quarries. Of the energy used to construct a building, around 80 % is used in producing and transporting materials [9]. Some of these materials, namely plastics, aluminium, copper, steel, glass, cement, ceramics, etc., are obtained using energy intensive processes, having a negative impact on the environment [2].

The embodied energy per unit mass of material is not in itself an indicator of its environmental impact, as the different materials present significant differences in terms of efficiency when used for the same purpose, so it is much more important to consider how much material is needed for any particular purpose. Another important factor to consider is the useful lifetime (durability) that the materials offer in different environments. A long useful lifetime may compensate for high energy consumption and vice versa [10].

Energy consumption when buildings are used, mainly for lighting, operating equipment and for air conditioning, can be higher than the energy used during the building stage [10]. This energy consumption can be largely controlled with decisions made by the designer and should be planned during that stage of the project, as the primary sources of energy used are non-renewable, for example, natural gas, oil and coal, etc., besides increasing greenhouse gas emissions. In commercial buildings, especially those with a central air conditioning system, the use of more efficient equipment combined with a suitable frontage can reduce energy consumption by up to 50 % [8].

In order to reduce the environmental impact of energy consumption, for example, reducing greenhouse gases, the EU has been promoting energy produced by renewable sources. Of all renewable energy sources, photovoltaic solar energy has the most potential for the construction industry, as it can be conjugated with city structures, enriching their architectural style. Besides this, there are other advantages, such as great functional versatility, as it can replace other construction materials in buildings, avoid losses in transport and distribution networks (medium voltage) due to production being carried out at the point of consumption, as well as the ability to locally supply energy at peak times.

18.2.1.3 Pollution

The construction industry also produces different types of pollution. The formation of gaseous emissions consisting of toxic gases, CO_2 and dust particles, liquid emissions and solid waste occurs in almost all activities in construction, from the extraction of raw materials to the transportation and production of materials such as cement, concrete, etc., during the usage stage and demolition [3]. The impact due to increased emission of greenhouse gases, namely, carbon dioxide (CO_2), halogen compounds (chlorofluorocarbons—CFC, and hydrofluorocarbons—HFC), methane (CH_4) and nitrous oxide (N_2O), some of which with very long residence times in the atmosphere, is significant not only for ecosystems but also for people, due to the resulting climate change.

The construction industry may be viewed as being one of the largest sources of pollution, particularly due to the production of construction materials. It is the third biggest contributor to CO_2 emissions within the industrial sector on a global level and within the EU [1], representing around 10 % of total CO_2 emissions. Most of these emissions are released whilst producing concrete, the most used construction material in the whole world, made using Portland cement. For CO_2 emissions from concrete production, around 85 % comes from cement production, with the remainder from transporting raw materials and the final product.

The processes for cement and lime production release CO_2, as they involve the calcination of limestone which is a thermal treatment process, in which the following reaction occurs:

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)} \tag{18.1}$$

Excluding the CO_2 corresponding to the burning of fuel needed for the process, for every tonne of quicklime produced (CaO), around 786 kg of CO_2 is released into the atmosphere or 595 kg of CO_2 when 1 t of hydrated lime is produced ($CaO{\cdot}H_2O$) [1].

Depending on the fuel and efficiency of the process, producing 1 t of clinker using the dry method produces approximately 820–870 kg of CO_2. Of this, 66 % comes from the calcination of limestone, with some of that absorbed in the carbonation of concretes and mortars [1, 7]. The use of fossil fuels to produce energy generates around 390 kg of CO_2.

During the building work, there are also other aspects, such as the application of asphalt, lead-based paints, etc., or water contamination from cleaning the mixer trucks at the end of the day, that are less significant but also important from a pollution perspective.

In addition to sound pollution, work yard activities also generate particulate matter that can be inhaled and is considered a big source of air pollution. Nevertheless, it is essentially the demolition phase that produces the most dust.

Inside buildings, when they are in use, there is also environmental pollution due to the concentration of some gases formed of volatile organic compounds, pathogenic microorganisms, dust, airborne particles, fibres, etc., released from the ground, materials, cleaning products or from activities involving the use of equipment, in particular the leak of CFC refrigerant fluid used in most air conditioning devices.

The presence of pathogenic microorganisms is usually associated with water produced by infiltration or evaporation related to poor ventilation.

The level of pollution inside buildings can be controlled by the selection of materials, the rate of ventilation (air renewal), particularly the air conditioning systems and ventilation, and the cleaning activities and asepsis.

Materials should be selected based on the amount of volatile organic compounds they release and also the cleaning they require. The most important organic compounds released include formaldehydes, organic compounds from glues, paint, plastics and other organic coatings. Inhalable fibres can come from coatings, such as plaster and stucco, carpeting, thermal insulators, and from the abrasion of pieces containing dangerous fibres, for example, chrysotile, used in the production of asbestos. The effects of these pollutants depend on the type, intensity and exposure time.

18.2.1.4 Waste

In spite of construction being a big cause of environmental pollution, there are many ways in which it can operate as a large-scale recycling industry not only for the waste this sector produces, construction and demolition waste (C&DW) but also waste/by-products from other industries [11–13]. In many developed countries, the constantly rising cost of raw materials and the depletion of natural resources have increased the reuse/recycling of waste as a potential alternative in the construction industry.

Construction consumes a huge range of materials, for example, plastics, plant-based products, different metals, composites, siliceous materials, etc., for different uses and different project types [14]. This fact has encouraged the construction industry to develop and seek alternatives for using waste, including plastics, glass, natural fibres and others, such as aggregates or mixed, promoting the development of new products that have physical characteristics and mechanical properties that are at least similar to conventional materials [15].

In the construction sector, the use of waste/by-products from other industries instead of natural raw materials to build roads, produce cement or alternative building materials that can replace conventional materials, both for economic and environmental reasons, helps reduce pollution and the extraction of natural resources from the Earth's crust [16].

For example, siliceous materials can be produced with waste that contains silicates in its composition, specifically fly ash from power stations, ash from municipal solid waste incinerators, granulated blast furnace slag and dust from electric arc furnace from steel plants.

The cement industry can also recycle fly ash and granulated blast furnace slag with basic index. Using waste in cement production, for example, replacing 50 % of Portland clinker with granulated blast furnace slag, will not only reduce energy consumption by 40 % but will also markedly reduce the volume of CO_2 released during the production process, thus helping to reduce the greenhouse effect.

The steel sector is also a big recycler of scrap steel in electric arc furnaces, producing steel that can be used to make reinforced concrete. Producing steel in an electric arc furnace consumes just 70 % of the energy needed for production using natural resources and saves natural raw material consumption by around 90 % (iron ore) limiting the amount of waste and CO_2 produced; the production of 1 t of pig iron releases 2.2 t of CO_2.

For the glass industry, the environmental impact of using glass scrap as a raw material for producing glass is smaller, but it does reduce energy consumption by around 5 %.

Finally, in addition to the aspects covered, the use of waste often enables the production of materials with better technical characteristics, as is the case with adding granulated blast furnace slag during cement production, which improves the performance of the concrete against corrosion from chlorides.

18.2.2 Life Cycle Analysis of the Construction Industry

Awareness of environmental problems led society in general to change patterns of consumption, becoming more likely to buy or use products and services that respect the environment, from its production from raw materials to the post-consumer stage.

In order to put into practice a suitable system of environmental management in the construction industry, a systematic analysis of all activities undertaken is required, using analytical tools, such as Life Cycle Analysis (LCA) [17–19].

The ISO standard 14040 defines the principles and framework of LCA. According to this standard, LCA is a relative methodology which compiles the inventory of relevant inputs and outputs associated to a product, process or activity in general, within well-defined limits, and evaluates the potential environmental impacts associated with those inputs and outputs, being the results of the inventory and impact phases interpreted in relation to the objectives of the study [20]. LCA defines emissions into the environment, namely gases, liquids and solids, according to the requirements and guidelines specified in ISO standard 14044 [21]. The requirements and guidelines are dependent from the goal and scope.

The study includes the complete life cycle of the product, process or activity, including the extraction and processing of raw materials, production, transportation, distribution, use, reuse, maintenance, recycling and final disposal of the waste that cannot be processed further for recycling.

In this model, defined as a 'closed loop', a 'cradle to cradle' analysis is undertaken where all the resources used are optimised, the waste production kept to a minimum, as well as ensuring that the products have an acceptable environmental performance, not intended for landfill but for being used again as raw materials for recycling, creating new products that are identical or different [22].

The construction industry's working products are buildings and public structures. The stages that constitute the life cycle of this sector range from extraction of the raw materials or transformation of the resources needed for the production of materials that will be used for the whole process, to the construction phase, use during its lifetime, which includes altering and remodelling buildings or repairing and refurbishing constructions, and the (full or partial) demolition stage of the buildings and infrastructure.

Problems associated with extraction, processing and use of raw materials and components used in construction, energy, waste production and environmental effects, as well as the potential reuse of products after their useful lifetime, and recycling and/or waste disposal, will be analysed throughout all stages of the life cycle.

Figure 18.1 shows a block diagram with the life cycle stages of materials in the construction industry, using a 'cradle to cradle' approach being the environment the boundary of the system. The blocks are connected by arrows that represent flows of energy and mass.

The input flows (mass and energy) represent the resources that can be extracted from the Earth to support the system. Calculating these input flows provides the information required to analyse the principle of sustainability using renewable resources, which implies that these are used at levels equal to or below those needed for their regeneration.

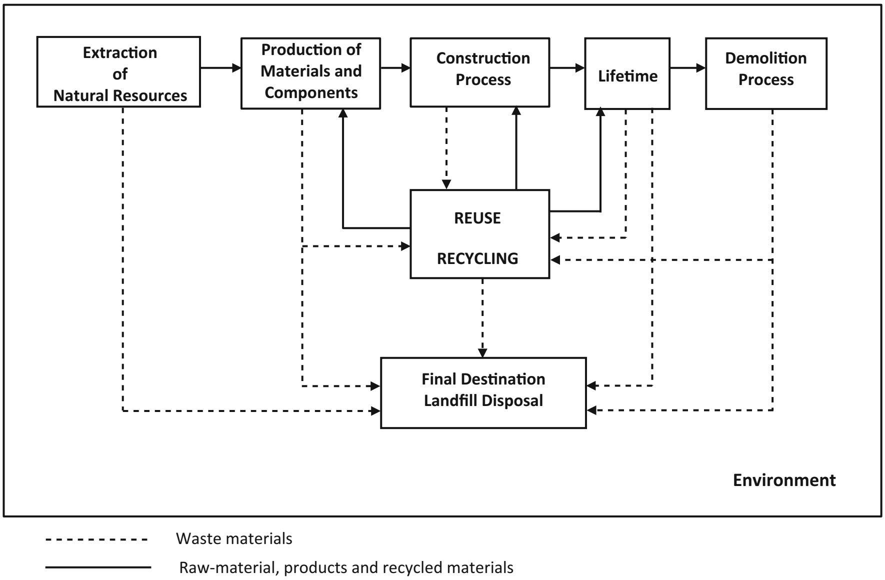

Fig. 18.1 Block diagram showing the life cycle of the construction industry

The output flows are, as well as being the useful product, the energy waste, solid, liquid and gas waste. The quantification of the emissions and waste gives an indication of the effects of pollution associated with the system [23].

The materials extraction phase is significant when assessing the environmental impact of the construction industry, due to energy consumption and use of natural resources for producing materials and products incorporated in this industry.

Interest in the LCA increased with the publication of legislation on environmental control, including integrated pollution control and better production techniques, the growth of the environmentally aware consumer market and the pressure from voluntary associations.

There are different IT tools, such as the SimaPro program [24], that calculate the LCA of processes and products.

In the flow chart for the construction industry, it is important to note the recycling of waste from different life cycle stages, with the recycled materials used again in the construction industry.

The final account of the environmental performance of the construction industry should take into account the waste from construction that can be used in other industries, and the construction industry should also use lots of materials produced using waste from other industries [2].

18.3 Integrated Waste Management

18.3.1 Introduction to Waste-Related Problems

Currently, our society faces many problems associated with environmental management, such as the conservation of natural resources, waste management and reducing the amount of pollutants released into the atmosphere.

In terms of waste, these should not be purely assessed based on the negative environmental impact, as there is also a big economic factor, due to the fact that they can be considered as a source of secondary raw materials.

However, the type of waste management normally used consists of landfill disposal, without any pre-sorting operations, as well as dumping on open land, which is not only bad for the environment but also for public health [25]. Disposal in landfill should be the last option due to the innumerable disadvantages it presents, namely, using and contaminating the soil, impact on ground water, landscape degradation, decreased quality of life and loss of material, causing higher consumption of natural resources [26].

Integrated waste management is one of the emerging holistic approaches to environmental and resource management, based on the concept of sustainable development. Generally, in an integrated waste management system, the treatment options when waste or a product reaches the end of its lifetime are hierarchical, as shown in Fig. 18.2 [27].

The order of priorities for waste treatment operations aims to minimise not only the impact of these on the environment but also preserve the natural resources available [28, 29].

The treatment operations should be analysed as a set of options being used in each situation, those that, through LCA, have a better ‘cradle to cradle’ environmental performance [22, 23, 30].

Besides being a form of pollution, waste also represents a significant loss of resources, which is why full priority should be given to minimising the reduction on the source (prevention and reduction), followed by reusing products. After these options comes recycling (including composting) and energy recovery which includes heat recovery, incineration, as well as other thermal methods, and the

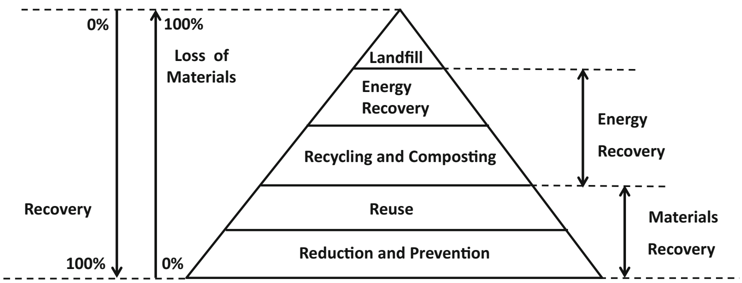

Fig. 18.2 Hierarchy of waste management operations (adapted from [27])

use of landfill gas. Finally, there is the least favourable option for final disposing of solid waste, landfill, due to the loss of the potential value of some components and the fact that it takes up large areas of land [23].

Waste prevention consists of a set of measures which aim to reduce the amount and hazardous nature of materials or substances it contains, both for the environment and for public health.

The concept of waste reduction is not new, and in simple terms, it refers to the strategies and technologies used to reduce waste generation, not including other resources, such as energy, water, etc.; it is sometimes confused with prevention.

Waste production is inevitable because in economic processes, including extraction activities, industrial production and services, there are always losses or waste that produce by-products. Even if the process is optimised, there will be losses and waste. In terms of consumer goods, the lifetime is always limited, turning the product into waste.

Once waste has been produced, the first stage consists of reusing it or reintroducing it into the production/consumption circuit, either being used for the same purpose for which it was originally made or for another use/function without being changed in any way. Reuse has economic advantages, as it reduces the use of materials and energy and reduces the quantity of waste to be disposed of, despite needing the use of logistical infrastructure.

Waste recovery is an option that requires processing (recycling) also requiring industrial infrastructure and logistics with in-built costs. It not only aims to recover materials but also energy (used as a fuel) that can present economic advantages, according to the cost/benefit ratio. Using waste as a raw material reduces the use of non-renewable natural resources and energy to produce materials, and it reduces the end volume of waste, thus reducing the area of land needed for landfill and the costs associated with waste disposal.

The main and most visible environmental contribution of recycling is the preservation of natural resources, which are replaced by waste, prolonging the lifetime of natural reserves and reducing the destruction of the landscape, flora and fauna [31].

Recycling waste is essential for sustainable development, as it closes the cycle of materials (‘cradle to cradle’ analysis), introducing them again in the productive process [22].

Making the decision to recycle waste is something that should be decided on carefully, and all the alternatives associated with using raw materials and energy should be considered, as well as the loss of product quality which may occur during the process, all of which are subject to market laws, with all the constraints that arise from them.

Waste disposal can be done by incineration without energy recovery, permanent storage, for example, in containers in mines, and landfill.

Permanent storage is only a controlled solution that needs a logistical infrastructure, and as well as being costly, it does not offer any kind of waste recovery; it has environmental benefits but no economic benefits.

Landfill represents, indefinitely, the waste of a finite resource, land, space which is increasingly valuable, especially close to large urban centres.

Landfills for hazardous waste concentrated chemical substances at levels that become dangerous and can contaminate the groundwater due to the reaction with the rain water. Many wastes are unstable so landfills pose a risk which remains active for hundreds of years [32].

The different management approaches presented here are not mutually exclusive. As waste is something that is quite heterogeneous, not only because of its origin but also due to the contaminants involved in the production and handling process, sometimes it is more logical to use different solutions for different parts of the waste, reusing the 'good' parts, recycling the 'partially damaged' parts and incinerating or sending to landfill the very contaminated parts [28].

With the aim of ensuring waste is appropriately treated and promoting whenever possible its recovery in reusable and recycled materials, appropriate legislation has been published by the relevant bodies all over the world.

18.3.2 Legislative Framework

The European Council has had an increasing influence on the management of solid waste, developing various environmental initiatives between 1973 and 1976 with the main aim of controlling and preventing pollution.

In order to ensure protection of the environment and improved quality of life, Directive 75/442/EEC was established on the 15 July 1975, establishing a number of standards with the aim of ensuring not only the disposal of waste but also encouraging waste recovery and reuse in general, to preserve natural resources.

This policy remained in force until 1991, when on the 18th of March the European Council adopted Directive 91/156/EEC which amended 75/442/EEC. This directive aimed to make waste management more efficient through prevention, harmonising legislation at European level, encouraging the reuse and recycling of waste as an alternative to natural resources and ensuring that the European Community and each member state (MS) becomes self-sufficient when it comes to waste disposal.

For the last (VI) environmental action programme (2001–2010), plans were developed for the sustainable use of natural resources and the management of secondary resources (waste), exploring possibilities to reduce waste and the harmful effects of waste. The programme took into account the fact that reuse and recycling processes should be improved, lengthening the life cycle of the materials. It stipulated targets for reducing the amount of waste sent to landfill, 20 % in 2010, aiming for a reduction of 50 % by 2050, as well as making it compulsory for EU MS to establish waste prevention programmes by 12 December 2013.

On 3 May 2000, under Directive 2000/532/EC, the Commission established the European List of Waste (ELW) (previously the European Waste Catalogue—EWC), which covers all types of waste produced in the EU.

The European Parliament and the European Council published Directive 2006/12/EC which revoked Directive 75/442/EEC, adopting the text of Directive 91/156/EEC with almost no amendments.

In 2008, Directive 2008/98/EC was published, on 19 November, aiming to harmonise legislation at European level, clarifying the definitions used and providing a practical application for the hierarchy of waste management. This waste directive established quite ambitious recycling targets for C&DW, stating that in 2020, 70 % of C&DW produced in the MS will be recycled.

Some EU countries have created regulations and taken initiatives to promote the correct management of this particular waste stream, in order to guarantee environmental protection.

Several countries in Western Europe, namely Germany have introduced C&D waste management in their legislation, after implementing the EWC which entered in force on 1 January 2002. The demolition contractors have a special responsibility in the C&DW management process, recovering and processing end of life materials and reintroducing waste into the construction market [33].

Legislation in the United Kingdom related to the integrated management of C&DW includes the use of this waste not only in construction but also for the production of aggregates [33].

In Scandinavia, the management of C&DW is very similar with the policies that have been adopted by the Western European countries. In Denmark, the municipalities are responsible for collecting C&DW, having more than half of introduced specific regulations on the sorting of this particular waste stream [33].

In Southern Europe, the situation regarding C&DW management is more complicated. In Portugal, the construction industry does not have a tradition of reusing or recycling the waste it produces, with most of it going to landfills or being disposed of illegally [34]. Legislation for regulating the production and management of C&DW stream was approved in 2008 and was very important not only for the large quantities produced of this specific type of waste but also due to the frequent illegal disposal of C&DW which has to be stopped.

The legal system for waste management was approved in Portugal for the first time through Executive Law no. 488/85, which encouraged reduced waste production, the development of technological processes for waste recycling and the removal of non-recycled waste, using their energy potential.

With the publication of Executive Law no. 239/1997 of 9 September, regulations were established for national waste management, with the disposal of waste in landfill regulated by Executive Law no. 52/2002 on 23 May.

In 2004, Directive 2000/532/EC on the ELW was replaced in Portuguese law by Ordinance 209/2004 of 3 March.

With the publication on 5 September of Executive Law no. 178/2006, which instituted the general law on waste management, Executive Law no. 239/1997 was repealed. Executive Law no. 178/2006 defines C&DW as waste from the construction, rebuilding, extension, alteration, conservation, demolition and collapse of buildings.

In spite of the legislation applied to waste management since 1985, the first specific regulations on managing C&DW were only published in 2008, through Executive Law no. 46/2008 of 12 March, which included prevention, reuse and collection, transportation, storage, sorting, treatment, recovery and disposal. However, whenever there is some point on C&DW management that is not specified in the aforementioned executive law, the relevant executive law on waste management is applied.

Producers and managers of C&DW should comply with the legal provisions which apply to the specific waste stream contained in the C&DW, specifically packaging waste, waste from electrical and electronic equipment, used oil, used tyres and waste containing polychlorobiphenyls (PCB).

Responsibility for managing C&DW defined in Executive Law no. 46/2008 is attributed to:

1. All stakeholders involved in the life cycle, from the original product to the waste produced, in accordance with the involvement they have.
2. Producers of C&DW (project managers and contractors), for buildings subject to licensing or prior notice under the legal terms of urbanisation and construction.
3. Bodies responsible for managing municipal solid waste (city councils), in the case of private projects without a licence or prior notice under the legal terms on urbanisation and construction.
4. Holders of C&DW, when it is not possible to identify the producer of these.

However the responsibility for managing the C&DW of the aforementioned bodies ends with:

1. The C&DW is delivered to facilities or those in charge of waste management who are duly licensed.
2. Responsibility is transferred to bodies responsible for managing waste flows.

This executive law also regulates the following actions:

1. Hierarchy of management for C&DW which prioritises reuse of C&DW in construction followed by sorting on point of origin of C&DW. If sorting is not possible at the point of waste production, it can be undertaken at a site involved with the project. Based on the hierarchy, C&DW is sent to licensed operators for this purpose.
2. Compulsory sorting prior to disposal of C&DW in landfill.
3. Use of C&DW in construction provided it meets the requirements of the national or European technical standards.

On 17 June 2011, Executive Law no. 73/2011 was published, which amends the general law on waste, and Directive 2008/98/EC was enforced on 19 November by the European Parliament and the Council. This executive law considers it a priority to prevent the production of waste and promote reuse and recycling, with the aim of prolonging its use in the economy before returning it to nature. Furthermore, it is considered important to promote the full use of the new organised waste market (OWM), as a means of consolidating the recovery of waste, with advantages for economic agents, as well as stimulating the use of specific waste with a high recovery potential.

Outside EU, in the United States, C&DW management is not covered by federal legislation since most materials constituting these residues are not considered hazardous material. Legislation varies across the states according to their characteristics, namely, annual rainfall and temperature range, land availability, geologic stability and policy related to the risk that C&DW can create on human health and the environment. This legislative autonomy has led to contradictory regulations throughout the nation. Twenty-three states have specific landfills for C&DW separated from MSW; in other states, landfills for C&DW are the same as inert debris landfills, non-MSW or MSW landfills or general solid waste facilities [35].

In Japan, the Construction Material Recycling Law requires sorting and recycling of specified materials (wood, concrete and asphalt) of C&DW. If a company wants to work in the demolition business, it should be registered by the prefectural government [36].

18.4 Construction and Demolition Waste

18.4.1 Introduction

The construction industry is considered the biggest producer of different types of waste, of all of society, with C&DW representing almost 31 % of all waste produced in the EU [37].

The source of construction waste varies a lot. Waste may come from construction losses or changes to buildings, from demolished buildings and asphalt streets, from disasters involving building collapse or damage, from excavation and clearing of land or from natural disasters, and as a result, it is very heterogeneous [38].

In any production process, there is always a certain volume of waste that is associated with the technological characteristics of the process. When the amount of loss is over the typical minimum limit for the technology used, it is considered to be waste. For the same technology, the amount of loss varies with regional characteristics and also time, so it is difficult to establish a set figure associated with the process and the wastage [39].

Loss occurs at different stages of the construction industry life cycle. The project stage is fundamental, as choosing inappropriate technology can increase the amount of waste, as can overestimating the size or building a structure that is not needed. Nevertheless, losses caused by inadequate planning are only apparent during the construction stage.

In renovation work, the amount of waste produced is associated with the lack of a culture of reusing and recycling C&DW as a construction material and not due to the waste of materials.

In demolition work [40], the amount of waste produced can be predicted and is not directly related to the processes used or the quality of the sector. Nevertheless, the quality of the waste can depend indirectly on technology, the construction processes and the system of demolition used. Some construction and demolition systems can produce waste with greater potential for recycling, compared to others that consist of mixtures of materials and components where contamination may make reusing or recycling them difficult. Another problem associated with waste is its volume, giving an increased cost of treatment and deposition, especially of waste that is classified as hazardous.

There is no standard classification or statistics for waste in this sector, but the levels of waste in the construction industry are very high and depend on the intensity of the construction work in each country, the technology used and the rates of waste and maintenance required, making it difficult to draw comparisons.

The average levels of loss provide an estimate of construction material waste. Comparing the estimated mass of the building with the mass of the materials acquired to build it, it is estimated that around 20 % is wasted. Of the material wasted, approximately half is used in the construction process itself and the other half leaves as waste [41]; the materials that are rejected from construction work may be considered as ‘urban mines’ of raw materials.

Managing waste costs money; these costs are first associated with their removal and transportation and secondly related to buying the material needed to make up for losses and also for paying surplus labour costs, etc.

In Western Europe, around 80 % of all C&DW comes from maintenance and demolition work and the remainder from construction work [31]. According to the Environmental Protection Agency (EPA), in 2003, in the United States, 47 % of waste came from construction work and refurbishment and 52 % from demolition [42]. These figures not only reflect the relative importance of construction work, maintenance and demolition work for each economy but also the rate of loss of materials in both areas of construction work.

In 2005, the average production estimate of C&DW in the EU was 290 million tonnes, corresponding to 480 kg per capita per year, whilst for MSW, it was 390 kg per capita per year [43, 44]. The C&DW produced equates to 22 % of the total waste produced and is the biggest flow of waste in quantitative terms excluding waste from mining and agricultural activity. Of the total C&DW, 60 % is from earth from excavation and levelling work, this means that this waste does not need treating (apart from earth that is contaminated) [45].

In the United States, figures supplied by the EPA suggest an increase from 136 million tonnes of C&DW produced in 1998 to 164 million tonnes in 2003. The per capita production of C&DW in 2003 was 463 kg per year, whereas MSW was 720 kg per capita per year. This disparity in the rate of production of waste per capita in the North American economy can be attributed to lower waste production in construction activities or even to the smaller role of construction in the North American economy (4 % of GDP) [42].

In Portugal, in 2005, C&DW production was around 7.5 million tonnes per year with a per capita production of 325 kg per year [46]. As with other EU countries, this figure corresponds to around 22 % of the total volume of the country's waste. Most of this waste (95 %) is sent to landfill, taking up a bigger area than MSW [47]. The construction sector represents 4.9 % of the GDP.

The figures on the production of different types of waste vary depending on the bibliographical sources used. In the case of C&DW, the figures show a larger discrepancy, as sometimes the figures concerning this specific waste do not include the figures for excavation waste, asphalt and clearing vegetation.

Natural disasters or wars are other factors that can cause a significant increase in the volume of waste.

18.4.2 Waste Classification

The first waste classification was legally established by the EU in 2000 with the ELW. This list defines and classifies all waste produced in the EU, identifying those that are considered hazardous.

Waste is considered hazardous if it has properties that make it dangerous or pose a threat to public health or the environment. The factors considered in this classification include toxicity, flammability, corrosiveness, reactivity, pathogenicity, radioactivity, etc.

The ELW consists of 20 chapters essentially grouped by the type of activity and divided into classes and subclasses. Waste is defined with a six digit code, with each two digits representing the chapter, the subchapter and the type of waste.

C&DW is classified in the ELW with the code 170000, with the last four digits representing the type of C&DW analysed, as shown in Table 18.1 [Directive 2000/532/EC and Ministerial Order no. 209/2004 of 3 March].

As well as this classification, C&DW can be generically classified according to the type of work that gave rise, the type of material, how hazardous the components are and the final treatment it can be undergone [48], as shown in Table 18.2.

18.4.3 Characterisation of C&DW

The construction industry has accompanied the development of materials, incorporating them in projects, so the composition of C&DW has been changing over time.

For example, fibre cement or insulation materials used in older buildings contained asbestos, and they can no longer be used in construction because of their toxicity.

Table 18.1 Legal classification of C&DW [Directive 2000/532/EC and Ministerial Order no. 209/2004 of 3 March]

Code 17	C&DW (Including road building and excavated soil from contaminated sites)
17 01	*Concrete*, *bricks*, *tiles*, *roof tiles*, *ceramics and gypsum-based materials*
17 01 01	Concrete
17 01 02	Bricks
17 01 03	Tiles, roof tiles and ceramic materials
17 01 04	Gypsum-based construction materials
17 01 05	Asbestos-based construction materials
17 01 06[a]	Mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances
17 01 07	Mixtures of concrete, bricks, tiles, roof tiles and ceramics other than those mentioned in 17 01 06
17 02	*Wood*, *glass and plastic*
17 02 01	Wood
17 02 02	Glass
17 02 03	Plastic
17 02 04[a]	Glass, plastic and wood containing or contaminated with hazardous substances
17 03	*Bituminous mixtures*, *coal tar and tarred products*:
17 03 01[a]	Bituminous mixtures containing coal tar
17 03 02	Bituminous mixtures other than those mentioned in 17 03 01
17 03 03[a]	Coal tar and tarred products
17 04	*Metals* (*including their alloys*):
17 04 01	Copper, bronze and brass
17 04 02	Aluminium
17 04 03	Lead
17 04 04	Zinc
17 04 05	Iron and steel
17 04 06	Tin
17 04 07	Mixed metals
17 04 08	Cables
17 04 09[a]	Metal waste contaminated with dangerous substances
17 04 10[a]	Cables containing oil, coal tar and other dangerous substances
17 04 11	Cables other than those mentioned in 17 04 10
17 05	*Soil* (*including excavated soil from contaminated sites*), *stones and dredging spoil*
17 05 03[a]	Soil and stones containing dangerous substances
17 05 04	Soil and stones other than those mentioned in 17 05 03
17 05 05[a]	Dredging spoil containing dangerous substances
17 05 06	Dredging spoil other than those mentioned in 17 05 05
17 05 07[a]	Track ballast containing dangerous substances
17 05 08	Track ballast other than those mentioned in 17 05 07
17 06	*Insulation materials and asbestos-containing construction materials*
17 06 01[a]	Insulation materials containing asbestos
17 06 02	Other insulation materials
17 06 03[a]	Other insulation materials consisting of or containing dangerous substances

(continued)

Table 18.1 (continued)

Code 17	C&DW (Including road building and excavated soil from contaminated sites)
17 06 04	Insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05[a]	Construction materials containing asbestos
17 07	*Mixed construction and demolition waste*:
17 07 02[a]	Mixed construction and demolition waste or separated fractions containing dangerous substances
17 07 03	Mixed construction and demolition waste other than those mentioned in 17 07 02
17 08	*Gypsum-based construction materials*
17 08 01[a]	Gypsum-based construction materials contaminated with dangerous substances
17 08 02	Gypsum-based construction materials other than those mentioned in 17 08 01
17 09	*Other construction and demolition waste*
1709 01[a]	Construction and demolition waste containing mercury
17 09 02[a]	Construction and demolition waste containing PCB (e.g. PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)
17 09 03[a]	Other construction and demolition waste (including mixed wastes) containing dangerous substances
17 09 04	Mixed construction and demolition waste other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

[a]Dangerous substances

In the 1950s and 1960s, lead in pipes was replaced with copper, and with the large influx of workers to major urban centres, construction using reinforced concrete became widespread.

More recently, in the 1980s, with the widespread use of plastics in residential buildings—such as polyethylene (PE), polyvinyl chloride (PVC) and polystyrene (PS)—plumbing and door/window frames have also started to be made of PVC, and industrial and service buildings have begun to be built using steel structures. The lower fire resistance of these structures led to the need to protect the beams and pillars and install firefighting equipment made of materials that contain halogen elements and other dangerous chemicals.

Currently, parking garages built in building basements have led to an increase in the volume of soil and rock removed, which has become part of construction waste. The growing use of glass in office building and shopping centre façades will affect the composition of demolition waste in the future.

Human (sabotage or terrorism) or natural disasters (hurricanes, tornadoes, earthquakes) produce a mixture of waste that it is not possible to separate, such as asphalt roofs, linoleum flooring, dangerous materials, specifically asbestos, concrete (with and without metal reinforcement), filler material (earth, gravel, sand), miscellaneous material as well as demolition material. The heterogeneous nature of this waste means it cannot be sorted, so the materials cannot be reused or recycled.

Table 18.2 General classification of C&DW

Classification	Characteristics
Type of work	• *Construction waste*: waste from new construction works for buildings and infrastructure
	• *Demolition waste*: waste from demolition of buildings and infrastructure
	• *Repair work waste*: waste from refurbishment and repair of buildings and infrastructure
Type of material	• *Waste from structural concrete* (simple or reinforced)
	• *Waste from masonry*
	• *Waste from asphalt materials*
	• *Waste from vegetation and unwanted soil*
Dangerous nature (of this material)	• *Inert waste*: this includes waste from concrete, soil, mortar, bricks, roofing tiles, masonry, etc.
	• *Non-inert waste*: this includes waste from different packaging, plastics, wood, metal, glass, etc.
	• *Hazardous waste*: this includes waste from asphalt, used oil, tins of paint and solvent, asbestos, etc.
Final destination	• *Reusable waste*: waste that can be reused directly on the work site or on another, consisting of clean bricks, concrete blocks, stone façades, roofing tiles and metal, vinyl coating, wooden cupboards, balconies, stairs, piping/electrical equipment, carpets, clean insulation and wooden/front beams
	• *Recyclable waste*: waste that can be recycled, consisting of broken bricks, concrete or stone façades, ceramics and tiles, damaged or broken glass windows, wooden beams, trees, metal dividers, covering material, aluminium window and door frames
	• *Non-recyclable waste*: waste that, either due to its characteristics or because it is contaminated, cannot be recycled, particularly mixed waste that cannot be sorted, non-recyclable materials, such as asphalt, linoleum flooring, dangerous waste including asbestos, treated wood waste (cladding or door frames) wood shavings and wood contaminated by paint

Building road infrastructure has led to greater amounts of asphalt in waste, because of its use as a binding material for the aggregate particles in road surfaces and also as a waterproofing material in emulsions and bitumen membranes, thanks to their hydrophobic characteristics. This waste basically has the same composition as waste from disaster situations, further including more varied materials, such as already separated reinforcing metal, metal signs and road dividers.

The composition of C&DW depends on geographic location and varies from country to country. It depends not only on the materials used in building but also on the stage of development of the industry, that is, the quality of the labour force, the construction techniques and the use of quality control techniques in the production process, so it is very difficult to give a single profile for its composition.

According to Henrichsen [49], C&DW consists of 50 % concrete (simple or reinforced), masonry and mortar and 20–25 % excavated soil, gravel for flooring restoration, asphaltic material and other less significant materials.

Nonetheless, in Portugal, the part related to excavated soil and gravel of flooring restoration represents 40 % (weight) of C&DW, the percentage being higher than the concrete, masonry and mortar part (35 %), contrary to the results presented by Henrichsen. Further to these parts, there are also some significant parts consisting of asphalt (6 %), mud from dredging and drilling (5 %) and metals (5 %) [34, 50].

In both studies, the inert part of C&DW represents at least 2/3 of all waste produced.

The fraction corresponding to inert material is considered the most important, because of its chemical and physical characteristics and its potential for recycling. This fraction is composed essentially of concrete waste from demolitions and consists of concrete made of hydraulic cement, whose weight composition is at least 95 % of concrete, a maximum 5 % petreous material and 1 % bituminous material, in the form of coarse aggregate (material with a particle size between 38.1 mm and 4.75 mm), fine aggregate (particle size less than 4.75 mm) and cement paste. Concrete represents around 75 % (weight) of all construction materials and is responsible for the largest proportion of waste from demolitions. As well as this fraction, C&DW contains other non-inert mineral materials such as chlorides, sulphates, organic matter and lightweight industrial products (paper, plastic, cloth, rubber, etc.), steel, aluminium, iron, glass, etc. It may also contain plaster and other material such as soil, mixed material and vegetation waste from earthworks or clearing land and building works.

In terms of masonry waste, there are several types, according to the level of purity, and it is predominantly composed of blocks, bricks, clay pieces, roof and wall or floor tiles, glass, etc.

The composition of C&DW in Europe is very different to the composition in the United States. In the United States, the wood content (treated and untreated) in the mass of construction waste is around 30 %, followed by covering materials (20 %), and blocks of masonry and concrete, between 1 and 8 % for residential buildings and 10 and 20 % for commercial buildings. Green waste counts for the smallest percentage (2 %) [49].

Compared to other types of waste, the volume taken up by C&DW is large, but as it is normally considered inert, it does not create concern for public or environmental health because of leaching from its components, the propagation of toxic materials or problems with organic matter rotting, as is the case for municipal solid waste (MSW). There is little data in literature about the individual nature of each of the components of C&DW that may cause damage to the environment or lead to degradation of a new product and also on the synergy between components that may potentially contaminate the environment.

However, the classification of C&DW may be altered because of its heterogeneous nature and the relationship between its characteristics and the work that produced them; in other words, a particular work may produce inert waste, whilst another may have components, such as adhesives, paint, oil, batteries, biocides in treated wood and asbestos, that make the waste less inert or even dangerous. The chemical analysis of leachates from landfills has shown quantities of toxic substances that are higher than the limits established in legislation.

C&DW has variable physical characteristics that depend on its generation process and may have the shape and size of the building materials (such as sand or gravel), or irregular sizes and formats, such as pieces of wood, mortar, concrete, plastic, metal, etc. Waste from demolition work has, in theory, a larger particle size than waste from construction processes, which are formed mostly of finer components.

In spite of its heterogeneous nature, the vast majority of C&DW components have high mechanical strength, whereby studying the physical and chemical properties of C&DW is fundamental to using it as a secondary raw material to optimise the properties of the new materials.

18.4.4 Ecotoxicological Effects of C&DW

C&DW may have a negative effect on public health and the environment if it contains dangerous components, such as asbestos, lead-based paint, coverings, adhesives, resins, plasterboard and tar creosote.

Lead-based paint aims to increase durability and speed up drying time. Contact with this type of paint can cause damage to the nervous system and cause developmental delay.

Tar creosote is used to preserve wood exposed to outdoor. Ingesting large quantities of creosote can cause mouth burns and stomach pains. If it comes into contact with the skin, it can cause irritation.

In the civil construction industry, asbestos has been used to increase the mechanical strength of cement and plastic, for insulation, fire protection and sound insulation. Asbestos is a group of natural minerals made of hydrated silicate and is composed of long, fine fibres that can be easily inhaled by humans. Regular exposure to asbestos can cause illnesses like asbestosis, mesothelioma and lung cancer, amongst others. Recognising the danger to public health posed by asbestos led to a decrease in its use during the second half of the twentieth century.

The problems with asbestos are related to eliminating it. The problem of the risk to public health is decreasing because the waste that is considered dangerous is being removed before buildings are demolished.

In the EU, in accordance with the ELW, asbestos is classified as dangerous waste and must be processed at special waste treatment facilities. The use of asbestos has been banned in the EU since 2005.

18.5 Recovery of C&DW

18.5.1 Introduction

The reuse of waste in the construction industry has existed since ancient times (the Roman Empire and Ancient Greece), where materials from demolished buildings were used to build new ones. Leftovers from tiles, bricks and lumps of ceramic were used without any treatment (with a large particle size) to produce rudimentary concrete or were milled and used as binders, taking advantage of the pozzolanic properties of ceramic materials.

In Germany, in the nineteenth century, the remains of concrete blocks were used to make artefacts. In Europe, following the Second World War, construction waste was recycled, since the demand for building materials was greater than reserves at the time.

In the last decades of the last century, economic and environmental reasons, such as the depletion of natural inert materials, led to several countries adopting specific policies to effectively recycle C&DW, since they can substitute to a large extent the natural inert materials used to produce concrete, blocks and flooring bases. Nonetheless, there are still great disparities in the application of these measures between different European Union countries.

Sorting of construction waste is a fundamental operation in recovering them, through reuse and recycling. Management of waste by the builder, as well as showing environmental responsibility, is also economically advantageous, since it makes possible to reduce the costs from processes and products.

The construction sector, for the extraordinary physical volume of materials that it involves, is potentially the largest market for the reuse and recycling of C&DW, providing a larger economy of natural resources (raw materials and energy) and minimising impact on the environment, as well as encouraging greater sustainability. On the other hand, the possibility of this sector to be a route to explore the sealing of dangerous industrial waste has been considered, since a large number of construction products do not come into direct contact with the weather, which limits its effect on the environment [51].

Recycling waste will introduce alternative products to the market for the same function and perhaps more appropriate solutions for specific situations, with gains in the overall efficiency of the process. In this way, reducing the costs of producing an appropriate material for many applications in civil construction may help to reduce the costs of housing and road infrastructure, railways, dams, etc.

These new products have found several legal/regulatory, technological, economic, geographic and information barriers, not only from consumers but also from technicians, since it is commonly stated that the quality of products containing waste is inferior. This problem can only be overcome by long-term policies.

The difficulty in introducing new technology to civil construction is real. The impact made on the real estate work costs is small, due to the price of land and the existence of prescriptive standards that specify the use of a particular solution rather than a product's performance. The economic problem can be more easily overcome using technology, by developing products with competitive advantageous over traditional ones, and legally, by (a) using legislative actions that encourage market creation; (b) making it compulsory for a minimum amount of recycled material to be used in the production process of a specific product; (c) increasing the tax on waste disposal; and (d) reducing the cost of recycled products, through tax breaks for products containing waste or other incentives or risk sharing.

These measures were put into practice in the United States through the EPA, which defined the minimum waste content to be incorporated in production processes, for example, on the production of Portland cement (15 % fly ash and 25 % blast furnace slag). In the United Kingdom, studies are underway that aim to define the minimum waste content in the composition of certain materials and the introduction of improvements in the market of products containing waste, imposing a tax on all material sent to landfills, as well as making long-term contracts possible for waste recycling.

The existence of certification systems for products, from the point of view of technical and environmental performance, is one of the measures to be implemented to overcome the technical resistance faced by products containing waste.

Introducing new products to a sector as conservative as construction, which has little experience in technological innovation, must be done according to a carefully defined marketing plan. Financial viability is fundamental to every stage, since many products, although technically viable, never make it to the market because of financial viability. This factor should bear in mind the product's market value, which includes the costs of the recycling or landfilling processes.

18.5.2 Recycling Materials Contained in C&DW

Integration of C&DW in the production chain is done by recycling. Recycling plays a significant role in the economy, increasing its competitiveness, creating new business opportunities and even creating jobs, since it makes it possible to generate value from a product that was considered an expense.

Optimising this operation is, fundamentally, the result of selective collection of materials depending on their characteristics and nature.

The recycling rate for C&DW varies greatly from country to country, since it depends on factors such as the availability of natural resources, the economic and technological situation of the country and the distance to natural raw materials.

In 1990, the recycling rate for C&DW was an average of 28 %, but its value has grown. However, in some EU countries the rate is already high, specifically in Denmark 90 %, Germany 83 % and Holland 87 % [52], thanks to special initiatives, such as the landfill tax created in Denmark in 1990.

The environmental impact of recycling activities is not always satisfactory, since it depends on many different factors, such as the type of waste and the technology used. If these factors are not appropriate, it may be necessary to use energy and even raw materials to transform the waste, which could make the recycling process expensive.

The potential for recovering C&DW is high provided that it is properly managed, and up to 80 % may be recycled [53]. Although there are many material recycling systems, recycling C&DW is restricted to only some types of waste.

Recycling waste allows in most cases a reduction in energy consumption in producing a certain product, because often the materials already include energy, which is true for recycling steel, aluminium and also for blast furnace slag. Other times, partially organic waste may be a source of energy, as well as increasing the mass of the final product. This is the case for rice husk, which contains around 20 % ash that is predominantly silicon- based.

Disposing of waste in a landfill involves an increase in energy because of transport and managing the landfill.

During the construction stage, with the aim of avoiding the contamination of materials to be recycled, appropriate areas should be made or containers installed to separate the different materials to be treated.

During the demolition stage, separating and cleaning the waste can be made more efficient if done carefully, by hand, and piece by piece. This procedure requires a great amount of time, space and labour force, so faster demolition systems are normally adopted, giving rise to large quantities of waste composed of a mixture of material with different origins and characteristics.

Selecting a viable alternative for the recycling process is only possible with detailed knowledge about the waste, which includes an exhaustive characterisation of the chemical and microstructural composition, as well as the characteristics of the process that produced it and respective environmental impact.

The different materials that make up C&DW, because of their different characteristics, do not undergo the same recycling operations. For each type of waste, there are many technically viable recycling routes, and it is important that there are rules to simply identify the different options, not using preconceived ideas but rather the combination of objective characteristics of the waste and the requirements of the different applications.

The option chosen should be the one with the greatest market potential and that minimises environmental impact. At this stage, the decision is made using a more qualitative than quantitative analysis.

Metallic materials, such as steel, copper, aluminium, iron, brass and zinc, can be easily recovered and reintroduced into the production cycle without losing their properties.

Cardboard and paper, provided that they have not been contaminated with impurities, can be introduced into the respective production processes and can also be used in the manufacture of cellulose-based insulation.

Recycling plastics, provided they are separated, poses no problems. Nonetheless, recycling plastics is more problematic when they are mixed or combined with other materials to form composites.

Glass is easily recycled and is integrated into the glass manufacturing process. The only problem is that different coloured glass cannot be recycled together.

18.5.3 C&DW Recycling Plants

The operations and equipment used in C&DW recycling processes are very similar to those used for processing ores.

The fundamental unit operation is fragmentation, followed by the unit operations of sieving and magnetic separation.

Due to the heterogeneous nature of the waste, specifically in terms of size, waste is crushed, normally in successive stages, whereby particle size is gradually reduced until the materials are freed, and a material with the desired size is obtained. For economic reasons, it is normally desirable for the material to be crushed only once, and a material with a wide range of particle sizes is obtained, that is, the diameter of the particles varies from very small sizes to sizes of more than 50 mm.

The most commonly used crushing equipment includes jaw crushers, cone crushers and hammer mills. This equipment applies compressive, impact and abrasive forces to reduce the size of the waste particles and liberate the different components so they can be separated and recovered in other operations.

Jaw crushers are normally used as primary crushers, since they do not reduce very much the size of the materials and generate a large amount of coarse aggregate. The particles break because of the compressive forces applied. Generally, the processed material is subjected to further fragmentation by smaller jaw crushers or hammer mills.

The disadvantages of that type of equipment lie in the fact that they are very noisy, produce a large amount of coarse material and beams and pillars produce low-quality lamellar particles because they have very pronounced fracture lines that may produce weak points. It is difficult to break down reinforced parts, and it is almost impossible to fragment large-scale wooden pieces, since they normally cause the axes of the crusher to break.

This type of equipment is most appropriate for processing structural concrete waste, since it makes it possible to obtain recycled material with good particle size characteristics for use in concrete. It has the advantage of having low maintenance costs.

Cone crushers are the most commonly used because of their robustness; they process reinforced concrete pieces or wooden beams, applying low compressive and impact forces. They greatly reduce the size of the waste, producing considerable quantities of fine and coarse aggregate. Cubic particles with good mechanical characteristics are found, since the particles break along natural rupture lines.

Although they are not noisy, they are disadvantageous because of their high maintenance costs. It is the most suitable equipment for producing recycled material for use in flooring.

Hammer mills are used as secondary crushers and are normally used together with jaw crushers. They generally have a mesh at the output end, which stops larger particles from leaving the impact chamber. This mesh can be replaced by meshes with different sized openings, so that material with different particle sizes can be obtained.

The rupture system of particles is similar to that when the cone crusher is used, that is, the particles break along natural rupture lines, producing a large amount of fine particles.

In terms of collection and treatment of waste, there are two methods. In one, the waste is separated selectively by the type of material and undergoes pre-crushing at the site where it is produced, using mobile equipment. In the other method, the material is demolished and removed from the work site in a nonselective way and without any prior treatment and is later transferred to companies in the recycling sector, which take on responsibility for treatment of the material. In this case, the equipment is fixed.

The operations of a C&DW recycling plant include the following steps:

1. Receiving the C&DW

   - This stage involves a visual inspection and weighing on a weighbridge.

2. Sorting at the plant

   - In the case of reinforced concrete, the steel is separated from the concrete using a hydraulic hammer and clamp crushers and are then sent on for recycling.
   - The C&DW is subjected to checks for possible contamination, separating the contaminated material from non-contaminated material, because if contamination is found, it will affect the following stages.

3. Forwarding non-contaminated C&DW

   - Materials such as concrete, brick, ceramic or mixture of concrete, masonry and stone are sent for primary sieving, whose aim is to remove the pieces measuring 0–5 mm, which is normally formed of particles of plaster, organic matter and dust, and it is then sent for crushing.

4. Forwarding contaminated C&DW

   - Elements, such as wood, paper, metal, insulation, etc., are removed by hand or with the help of pincers, for example.
   - Afterwards, they are sent to the sorting unit, with vibrating sieves and magnetic separation.
   - Lastly, before being sent for crushing, the waste passes through a primary sieve, with the aim of removing pieces measuring 0–5 mm.

5. Crushing with sieving and magnetic separation

   - Crushing is performed by impact or jaw crushers, and the output material has a particle size between 0 and 80 mm. At the output from the crusher, the material passes through a magnetic separator to remove the remaining metal.

6. Storage

   - Materials are separated according to origin and main components.
   - Protection against the weather.
   - Avoiding segregation of materials.

The capacity and complexity of a recycling plant depend on the supply of waste and the demand for recycled inert material, as well as the characteristics desired for the product.

Recycling plants should be located as close as possible to urban centres, not only so that they are close to the sites that produce waste but also to be close to the users of recycled aggregate, thereby reducing transport costs and the costs of producing recycled materials. However, being located in urban areas may cause problems due to noise and dust emissions, causing resistance from local residents. These problems may be minimised, however, by adapting the equipment.

As the quality of recycled inert material depends on the quality of the original material and because waste is very heterogeneous, during processing, it should be subjected to a homogenisation operation.

As well as using suitable demolition techniques and carrying out a preselection of supply material, recycling equipment should be flexible and be prepared for a large variation in the materials' properties.

Material impurities should be removed manually before and/or during crushing, and ferrous metals should be separated using electromagnets. In the second sorting operation, lighter material is separated, followed by a second fragmentation and sieving. Finally, finer sorting is performed, either wet or dry, in order to remove friable particles, organic matter and other fine impurities, etc.

Using impurity separation techniques may increase dust emissions and generate new waste, whose final destination may increase the production costs of the recycling units.

This way, two types of waste processing can be used, either wet or dry, with dry waste processing plants being the more common of the two [54].

The equipment used in wet processing is more sophisticated and produces better quality inert material. In wet processing, further to the stages used in the dry method, there are other procedures designed to eliminate material with reduced specific weight. The water used in this process can be treated, thereby reducing its environmental impact and operating costs.

Wet processing should be used in plants with a high annual treatment capacity and a sufficient supply of construction materials for recycling, which only happens in large urban areas [54]. Initial investment and production costs are much higher than for dry processing.

The main properties of recycled material that are affected by the procedures and equipment used in the crushing process are classification and composition, impurity content, particle size, and the shape and resistance of the particles. For example, depending on the crushers used, the morphology of the particles can be cubic or lamellar and may have fracture lines.

There is no equipment that simultaneously provides optimisation of these properties. Therefore, the demolition and recycling of the waste should be adjusted in order to optimise the results from a technical and economic point of view for each case.

In any environmental management policy, the reuse of C&DW at the work sites that produce it should be encouraged. If this is not possible, the waste should be sent to licensed operators.

In Portugal, in order to properly refer waste and manage it suitably, the Portuguese Environment Agency (*Agência Portuguesa do Ambiente*—APA) has an Information System for Waste Management Operations Licensing (SILOGR) available on its site [46].

The information in that system relates to licences issued by the Ministry of the Environment and Urban Planning and the Ministry of Health, and the information system relating to licences issued by the Ministry of the Economy is being updated. It should be noted, however, that the data available does not replace or prevail over licences/permits issued by the respective licensing bodies.

This computer application's main objective is to facilitate access to relevant data on waste management operations, and after the user introduces the ELW code and the district desired, information is provided on operators licensed to collect the waste in question.

Licensed operators should comply with the legislation, which prohibits disposing of C&DW in landfills without previously sorting materials with a view to recovering them.

To meet the main needs of operators and agents in the sector, the APA makes available technical specifications, defined by the National Laboratory of Civil Engineering (LNEC), on C&DW and respective uses, which cover the most common potential uses in the civil construction sector.

18.6 Uses for Recycled Materials

Replacing traditional materials with materials produced using waste is only feasible when the properties are suitable for performing the function for which they are designed.

The use of C&DW should take place in accordance with the national and European technical standards applicable. In Portugal, in the absence of the abovementioned standards, the technical specifications defined by the LNEC are used, in accordance with Table 18.3 [55–58].

Table 18.3 LNEC technical specifications for the use of C&DW

LNEC specification	Recycled material	Use
E 471-2009 Guide to use of coarse recycled aggregates in the manufacture of concretes with hydraulic binders	• Coarse recycled aggregates	• Filler or blinding concrete, without a structural function, and in aggressive environments • Regular or reinforced concrete
	• Non-bound aggregates, natural stone and treated aggregates with hydraulic binders	
	• Bituminous materials	
	• Floating petreous material	
	• Clay-based masonry elements, calcium silicate masonry elements and non-floating cellular concrete	
E 472-2009 Guide to use of hot bituminous mixtures in plants	• Recycling hot bituminous mixtures in plants	• Wear layer • Base and blinding layer
	• Milled bituminous mixtures	
	• Plates taken from pavement layers, later reduced	
	• Surplus materials from the production of bituminous mixtures	
E 473-2009 Guide to use of recycled aggregates in non-bound road surface layers	• Crushed concretes	• Non-bound road surface layers (base and sub-base)
	• Aggregates from non-bound or cement-treated road surface layers	
	• Masonry	
	• Bituminous mixtures	
E 474-2009 Guide to use of materials from construction and demolition waste in earthworks and the bed layer of transport infrastructure	• Crushed concretes	• Earthworks and bed layer for transport infrastructure
	• Aggregates from non-bound or cement-treated road surface layers	
	• Masonry	
	• Bituminous mixtures	

The LNEC specifications provide recommendations and establish minimum requirements for the use of coarse recycled aggregates in the manufacture of concretes with hydraulic binders (E 471-2009) [55]; for the manufacture and use of hot bituminous mixtures in plants, using recovered bituminous mixtures (E 472-2009) [56]; for the use of recycled aggregates in non-bound road surface layers (base and sub-base) (E 473-2009) [57]; and for recycled materials from C&DW in earthworks and the bed layer of transport infrastructure, specifically roads, airports and railways (E 474-2009) [58].

Coarse recycled aggregates [55] come from construction, rehabilitation and demolition works for buildings or other civil engineering structures and are divided into three classes, in accordance with the proportion of the different components. The identification of these aggregates should contain, as a minimum, an indication of the producer and place of production, the class to which they belong and the size (particle size).

The materials produced with aggregates from C&DW whose composition is mostly concrete have been shown to have better properties (better mechanical strength, less water absorption, etc.) and are more uniform in their physical and chemical properties in comparison with materials produced using recycled aggregates composed mostly of masonry. This behaviour is related to the fact that concrete aggregate consists of a smaller number of materials (cement mortar and sand, crushed stone and additives for concrete) than masonry aggregate, so the latter are only used for concrete with few requirements.

Coarse recycled aggregates are used to manufacture concretes with hydraulic binders. Recycled aggregates cannot be used to manufacture concretes that will be in contact with drinking water. There are only two classes of recycled aggregates that can be used to manufacture concrete for use in regular or reinforced concrete elements. Nonetheless, in the case of reinforced concrete, the maximum amount of recycled aggregates for concrete is subject to limits.

For regular, filler or blinding concrete in nonaggressive environments, the amount to be included is not subject to any limits. The materials used for filler should be hard and have a narrow range of particle sizes, so that they are easily consolidated and keep their drainage performance. They should be chemically inert and have a stable volume in the presence of water. Masonry recycled material should not be used, since it may contain expansive material or wood, which after decomposing may leave voids in the filler.

The use of recycled aggregates from concrete in the manufacture of concretes with structural functions is also subject to some limitations, for example, in terms of the proportion amongst the aggregates used, so as to avoid possible variations in modulus of elasticity, creep, shrinkage and properties linked to durability.

In terms of chemical reactivity, recycled aggregates are considered to be potentially reactive. However, recent studies show that with the exception of recycled aggregates from floor blinding, recycled aggregates can be classified as nonreactive, even if they come from concretes manufactured using reactive aggregates.

No demands or rules were defined for the use of fine recycled aggregates, given that they generally contain a high proportion of elements with a particle size of less than 0.063 mm, which are damaging because of the greater adhering mortar content, their more angular shape and the fact that they have significant amounts of sulphates and other impurities, thereby requiring more water absorption to maintain workability and compromise the concrete's mechanical strength.

When good-quality material is desired for structural elements, only the coarse part of the recycled material from concrete should be used.

The elasticity modulus for concretes containing recycled material is generally lower than that for conventional concretes, even if the recycled material use is from concretes. This can be explained by the presence of mortar adhered to the recycled material, which has a lower modulus of elasticity and decreases the concrete's modulus. The specific mass of concretes containing recycled material is generally less than that of conventional concrete, due to the difference in mass of recycled aggregates. The tensile, flexion and shear strengths of concretes containing recycled material are also lower than those of conventional concretes, whilst creep, shrinkage and loss through abrasion have higher values.

Water absorption by concretes is linked to porosity and permeability. This is directly linked to the occurrence of carbonation. More porous concretes tend to have lower mechanical strength and are more susceptible to carbonation and chemical attacks. Because of their greater capacity for absorption, recycled material should be saturated before coming into contact with the binders to prepare the new product, because otherwise the aggregate may absorb part of the water needed for the cement to hydrate, damaging the quality of the material.

Shrinkage linked to the curing process for concrete produced using recycled inert material is higher than that of concrete produced using natural inert material because shrinkage values depend on the total surface area, and, in recycled inert material, the surface area is greater because of the presence of cement paste. Another aspect that may contribute to greater shrinkage for concrete produced using coarse recycled inert material is the greater deformability that this material has.

The durability of concrete made with recycled inert material is influenced by the factors mentioned, although the most significant is the presence of contaminants. The type of contaminant and the admissible content values depend on the type of use for the recycled material, being the amount of impurities greater for finer recycled aggregates.

One of the most damaging compounds in recycled aggregate is plaster, since sulphates may lead to the expansion of the new product. Chlorides may lead to steel corrosion, and some standards significantly limit their proportion in recycled material. Glass content should also be limited because alkali-silica reactions may take place when the new material is prepared and in contact with cement and with the presence of water.

Corrosion of the reinforcements in concrete made with recycled concrete takes place more quickly than in conventional concretes. The time that corrosion of steel bars begins is practically the same for concretes containing recycled material and conventional concretes, but if masonry waste is used, the time is slightly shorter. Once corrosion begins, the corrosion rate is the same regardless of the type of aggregate.

Using recycled aggregates in concrete is a promising alternative for civil construction, since natural inert material (sand and gravel) should be reserved for more prestigious uses, such as high-resistance concrete, and concrete without structural functions can be produced with recycled aggregates.

Another type of waste to be considered are the bituminous mixtures mentioned in [53], which come from the construction, rehabilitation, conservation and demolition of road and airport surfaces, known as C&DW. These mixtures may consist of milled bituminous mixtures, plates taken from pavement layers that are later disaggregated and/or crushed, or surplus materials from the production of bituminous materials. After recovery and after they have been kept separately according to origin, they should be stored carefully, protected from atmospheric actions, in order to prevent contamination and runoff.

The properties to be considered, when using recovered bituminous mixtures in the manufacture of recycled mixtures, are the material's maximum particle size, its nature (e.g. polluting components, namely, tar), shape, size and content, and the size of the aggregate contained in it, as well as the presence of extra matter, the characteristics of the recovered binder and the content of the binder. Further to these characteristics, the provenance of the materials should also be mentioned, in particular the works and type(s) of layer(s) from which they were extracted.

The rate for incorporating the recovered mixture depends on its characteristics and type of use, for example, if it is a wear layer or a blinding or base layer.

The tests carried out as quality control for the recycled mixture are similar to those performed for traditional bituminous mixtures.

Other types of recycled aggregates not included in [55] are those that come from construction, rehabilitation and demolition works for buildings, transport infrastructure or other civil engineering structures, also known as C&DW [57]. These aggregates may be formed of crushed concretes, aggregates from non-bound pavement layers, masonry and bituminous mixtures, and may be used as recycled aggregates in non-bound road surface layers (base and sub-base).

The recycled aggregates covered in this LNEC specification [57], for the purposes of use in non-bound road surface layers, are grouped into two classes, which depend on the waste's components, and three categories, which depend on its geometric and physical properties. The identification of these aggregates should contain, as a minimum, an indication of the producer and place of production, the class to which they belong and the size (particle size).

Recycled aggregates with larger particle sizes, when used in base and sub-base layer, may need to be mixed with natural aggregates, mostly with a view to correcting particle size.

The use of recycled materials from C&DW consisting of waste from construction, rehabilitation and demolition works for buildings, transport infrastructure or other civil engineering structures, is covered by LNEC specification E 474-2009 [58]. They may be used as materials for earthwork and bed layers for transport infrastructure, although they cannot be used in areas where they may come into contact with underground water or for drainage systems or in areas that flood frequently.

The alkaline level of this C&DW, concrete and masonry structures, is normally high, so they cannot be used in close proximity to materials susceptible to corrosion in that kind of environment, such as aluminium and galvanised piping.

The recycled materials covered by this specification are grouped into three classes, based on the relative proportions of each component, and two categories, based on geotechnical characteristics.

Just as for recycled materials established in the previous specifications, the identification of these recycled materials should contain at least an indication of the producer and place of production, the category to which they belong and the maximum particle size.

This type of recycled material, along with the recycled aggregates mentioned in [55, 57], should be stored separately, according to origin and main components, and can be used in combination with waste from different origins provided that they are mixed properly and under conditions that ensure homogeneity throughout the recycled material.

Conclusions

Sustainable development as a form of economic development, which uses natural resources and the environment in favour of today's society and future generations, is a real concern for the civil construction industry. These issues should modify the entire pattern of developing and assessing civil construction projects, making technicians responsible not only for the construction stage but also for the working life and demolition stages, minimising the consumption of non-renewable raw materials and water by using new construction technology and products.

The civil construction industry should try to close its production, material and energy cycle as far as possible in thermodynamic terms. The waste produced should, whenever possible, be reused and/or recycled, and any waste that is not recoverable should therefore be sent to landfills without posing a danger to the environment.

Recycling C&DW means reducing the quantity of materials disposed of in landfills, as well as less consumption of raw materials.

Recycling waste from other industries to produce materials for the civil construction industry should be investigated and is an important practice for sustainability.

Developing products that contain waste, some of which may be considered dangerous, is a multidisciplinary activity and needs to be done carefully and following criteria so as to ensure the success of these products on the market.

Introducing alternative products to the market for the same function and, possibly, more suitable solutions for specific situations, with increases in the general effectiveness of the process, will reduce production costs and may contribute to a reduction in the costs of housing and road and rail infrastructure, dams, etc.

The Waste Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 establishes a goal for 2020 that 70 % of C&DW produced in member states must be sent for recycling. Although there are no official statistics, it is unanimous that Portugal is still far from reaching this amount.

Executive Law no. 73/2011, which alters the general regime for managing waste, transposes Directive 2008/98/EC of 19 November of the European Parliament and of the Council and considers that strengthening the prevention of waste production and encouraging its reuse and recycling is a priority, with a view to prolonging waste's use for the economy before returning it to the environment. Furthermore, it considers promoting the full use of the new organised waste market (OWM) to be important, as a way of strengthening waste recovery, with advantages for economic agents, as well as stimulating the use of specific waste with high recovery potential.

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