4RinEU

Reliable models for deep renovation

D2.7
WP2

Guidelines and technology concepts for managing building end of life

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Foreword

Despite the low energy performances of the European building stock, the yearly renovation rate and the choice to perform a building deep renovation is strongly affected by uncertainties in terms of costs and benefits in the life cycle.

The project 4RinEU faces these challenges, offering technology solutions and strategies to encourage the existing building stock transformation, fostering the use of renewable energies, and providing reliable business models to support a deep renovation.

4RinEU project minimizes failures in design and implementation, manages different stages of the deep renovation process - from the preliminary audit up to the end-of-life - and provides information on energy, comfort, users' impact, and investment performance.

The 4RinEU deep renovation strategy is based on 3 pillars:

- *technologies* - driven by robustness - to decrease net primary energy use (60 to 70% compared to pre-renovation), allowing a reduction of life cycle costs over 30 years (15% compared to a typical renovation);
- *methodologies* - driven by usability - to support the design and implementation of the technologies, encouraging all stakeholders' involvement and ensuring the reduction of the renovation time;
- *business models* - driven by reliability - to enhance the level of confidence of deep renovation investors, increasing the EU building stock transformation rate.

4RinEU technologies, tools and procedures are expected to generate significant impacts: energy savings, reduction of renovation time, improvement of occupants IEQ conditions, optimization of RES use, acceleration of EU residential building renovation rate. This will bring a revitalization of the EU construction sectors, making renovation easier, quicker and more sustainable.

4RinEU is a project funded by the European Commission under the Horizon 2020 Programme and runs for four years from 2016 to 2020.

The 4RinEU consortium is pleased to present this report which is one of the public deliverables from the project work.

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Acronyms

EOL: End of Life
C&DW: Construction and Demolition Waste
Dfd: Design for Deconstruction
PMF: Prefab Multifunctional Façade
LCA: Life Cycle Assessment
BIM: Building Information Modelling
CPR: Construction Products Regulation
hENs: Harmonised European Standards
ETA: European Technical Assessments
EAD: European Assessment Documents
OSB: Oriented Standard Board
EPS: Expanded Polystyrene

Executive Summary

The objective of the guidelines is to define good practices to advise the manufacturers in relation to the sustainability of deconstruction processes. With this aim, specific disassembly approaches to manage the end-of-life of the buildings components, increasing the recycling rate of the construction materials for the proposed technologies, are defined.

The research activities performed for the drafting of the guidelines are the following:

- definition of approaches for quick identification and quantification of waste materials from the existing building components to be deconstructed, demolished or renovated;

- based on a life cycle oriented observation, definition of strategy for re-use and recycling of components and materials, including evaluation of costs and benefits as well as operative guidelines for (i) dismantling, detachment and transformation of construction waste in raw materials for further construction works or building components manufacturing (ii) regeneration of components for the same use in other buildings (iii) their disposal but minimizing the environmental impact;

- identification of best available technologies for recovery construction materials. Such technology solutions will make easier the managing of whole building or single component end-of-life, and the study provides information on how to manage the deep renovation, thinking on the building life cycle to reduce the actual construction waste also during the operative phase, acting on “planned maintenance” strategies;

- evaluation re-use in the same building of existing systems after deep renovation (e.g. window from existing wall to prefab façade).

The followed approach during the preparation of the guidelines required first of all a literature review in order to know the current situation in the EU regarding the assessment and management of the construction and demolition waste streams prior to demolition of buildings and infrastructures. In the process of defining the End of Life principles of the 4RinEU Guidelines applied to the refurbishment, demolition and recycling sector, several bibliographical sources as well as past and current research projects have been checked.

1 Introduction

The construction industry has been well accused for its enormous environmental impacts. In particular, construction and demolition waste generated from building and infrastructure-related activities form a major stream for municipal solid waste. Among various construction activities that generate building waste, building demolition and renovation appear to be most the contributory[1].

Today, building materials end up as waste when no longer needed, meanwhile destroying ecosystems, increasing environmental costs, and creating risks of resource scarcity. To create a sustainable future, the building sector needs to move towards a circular system, a pattern in which buildings and building materials can be reused, adapted and re-built several times. Whether an industry goes circular or not depends on the value of the materials within it – worthless materials are considered as waste, while valuable materials are usually reused or recycled.[2]

The Waste Framework Directive 2008/98/EC establishes a target of 70% of Construction and Demolition Waste (CDW) to be recycled by 2020. Therefore, the Communication on Resource Efficiency Opportunities in the Building Sector is especially focused on an increase of the use of recycled materials and the reduction of CDW. This communication is aligned with many documents or schemes:

- Raw Materials Initiative (COM(2008) 699) final launched in 2008 by the Commission aimed at boosting resource efficiency and promoting recycling,
- Roadmap to a Resource Efficient Europe (COM(2011) 571) which requires that buildings should be refurbished or built with greater resource efficiency
- Communication on “Strategy for the sustainable competitiveness of the construction sector and its enterprises” (COM (2012) 433 final).
- Communication "For a European Industrial Renaissance" (COM (2014) 014 final) claiming for the re-industrialization of Europe.

Considering the life cycle of a building it becomes obvious that the design phase is important, but it solely represent one step of the life span of a construction. Looking further, not only the design of a building has to meet criteria of sustainability, but also the phases of construction, use and deconstruction. There is a need not only to foresee and plan the future of construction, but also to reflect on methods how to integrate the present building stock into sustainable construction concepts. Consequently, sustainable principles should be far more integrated into construction processes. Up to now, the transition of the present building stock into high performance buildings is still characterized by open-loop material systems. Closed-loop systems with full materials recovery do not exist at present, due to a

[1] King Pun S, et al. Promoting the reuse and recycling of building demolition materials
[2] BAMB Project. Synthesis report on State of Art.

lack of technology, poor product design, thermodynamic reasons and caused by the lack of adequate economic incentives. Taking into account that dumping capacities are limited, land for landfill is reduced and natural resources, e. g. wood, metal and natural gravel, have to be preserved, it becomes obvious that closed-loop material systems have to be established[3].

Thus, one aim of advanced construction processes should be to keep as much construction materials in closed-loops as possible, respecting technical, ecological and economic principles. The material accumulated at the end-of-life of buildings can be brought back into the material flow, in the same or different condition and functionality, after recycling or recovery and can serve as input for new high performance houses.3

The sustainability of a building in terms of its material usage, construction, occupation and end of life is becoming an ever more important consideration. At the end of a building's life, it can either be demolished or it can be dismantled and the elements and materials reused and recycled. The most environmentally beneficial use of waste is to reuse it, since it is associated to higher reductions of embodied energy and emissions to air and water compared to recycling.

The low reuse and relatively low recycling rates reflect a number of barriers, including the fact that most building elements are not currently designed for dismantling and the resulting excessive time requirements for dismantling coupled with low disposal costs make dismantling a prohibitively expensive process. Demolition contractors report that deconstruction can take two to ten times longer than demolition efforts putting deconstruction at a distinct economic disadvantage[4]. However economics is not the only barrier to reuse and recycling. Even if a building material or element is capable of being dismantled from a technical and economic point of view, it still may not be reused or even recycled due to the lack of a market for uncertified products or those of lesser aesthetic appeal.[4]

The Waste Framework Directive 2008/98/EC aims to have 70% of Construction and Demolition waste recycled by 2020. However, with the exception of a few EU countries, only about 50% of C&D waste is currently being recycled[5]. To optimise a building overall life cycle, its end-of-life must to be considered from the very beginning: how the components are assembled and which materials are used determines the possible deconstruction approaches and whether re-use can be maximised. This is important both for the development of components and the overall deep renovation design project. Dialogue cross disciplines and roles is needed and end-of-life studies have to become a standard element of any renovation design.

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[3] Schultmann F., Sunke N. *Closed-loop oriented project management in construction*
[4] Sassi, P. Designing for dismantling, re-use and recycling
[5] EU Construction and Demolition Waste Protocol and Guidelines

The guiding principle for the 4RinEU end-of life strategy is the following priority scale:

1. Re-use components in the same building or other (circular economy perspective);
2. Re-cycle materials with the same function;
3. Down-cycle materials to be used for other purpose;
4. Manage demolition waste minimising its environmental impact.

The 4RinEU end-of life strategy, defined within the project both for the developed technologies and for the whole deep renovation design in the demo-cases, is transferred into guidelines to allow its application in any individual deep renovation project with 4RinEU packages. It includes (a) a check list for quick identification of waste material from the existing buildings, (b) the identification of technologies for recovery of materials, (c) strategies to optimise the end-of life of 4RinEU renovations and (d) strategies to optimise the end-of-life of components in the building-to-be-renovated.

The different end of life options for each material will be assessed in terms of their environmental impact. The product end-of-life needs to be considered from the beginning, during the design and installation phase, to facilitate and maximize the reuse/recycling. The decision-making process at the end-of-life of the building will follow the aspirations of the waste hierarchy:

(i) Waste minimisation activities through in situ building element/product reuse
(ii) Reclamation and the reuse of products ex situ
(iii) Recycling or heat recovery.

When creating a hierarchy among the end-of-life alternatives, according to environmental impact, the direct reuse of a product comes highest in the rank, followed by recycling. Moving towards reuse of products is an ideal solution for the product end-of-life approach in order to minimize the environmental impact.

2 End of life definition

In the process of defining End of Life principles applied to the renovation, demolition and recycling sector, several bibliographical sources as well as past and current research projects have been checked. The most important ideas taken from the literature review can be found below:

2.1 Building phases

According to the BAMB project[6] (Buildings As Material Banks), the building process consists of several consecutive steps that can be divided in phases. Different ways of describing and grouping of activities are possible and their complexity and timeframe depends a lot on the type of building project (e.g. small private house or large public building) and on the common practices in individual countries.

The analysis of a renovation process considered in BAMB project distinguishes 4 main building phases:

1. **Design**: the phase where all the financing, designing, planning is specified.

2. **Build:** the phase where the building or infrastructure is realized.

3. **Use & Operate:** the phase where residents/ users/ occupants, etc. are using the building and the building is operated to maintain the service levels required by the occupants.

4. **Repurpose & demolition:** the phase where transformation is planned, and products and materials are extracted. However, currently repurposing is not common practice and most end-of-use options of buildings lead to partly or complete demolition (i.e. the building as a demolition liability).

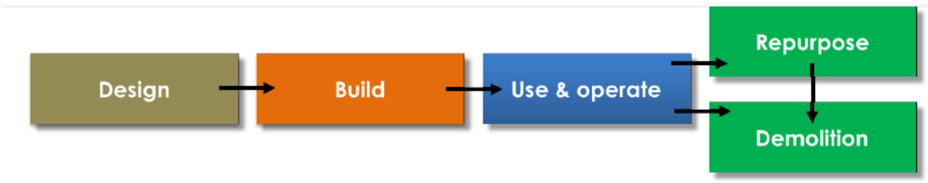

Figure 1: Building phases from a linear perspective (BAMB Project)

[6] www.bamb2020.eu

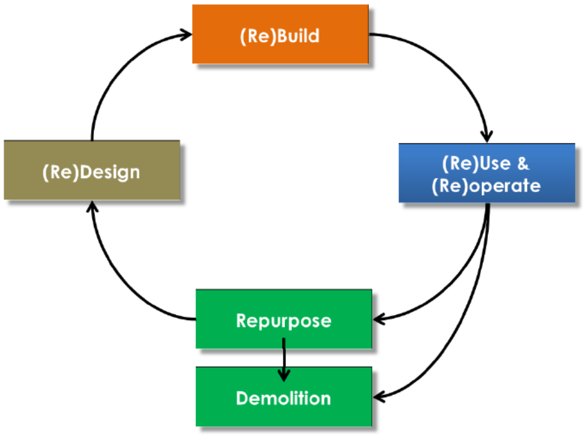

Figure 2: Building phases from a circular perspective (BAMB Project)

Although these four construction phases appear to have a linear dimension, the construction ecosystem is not linear, as there are many iterative links and loops between the building phases and between the different network participants.

When looking at repurposing of buildings and components, the process can be considered to be circular or continuous, as the phases of (re)design, (re)build and (re)use will be revisited multiple times during the life-time or usage of a building.

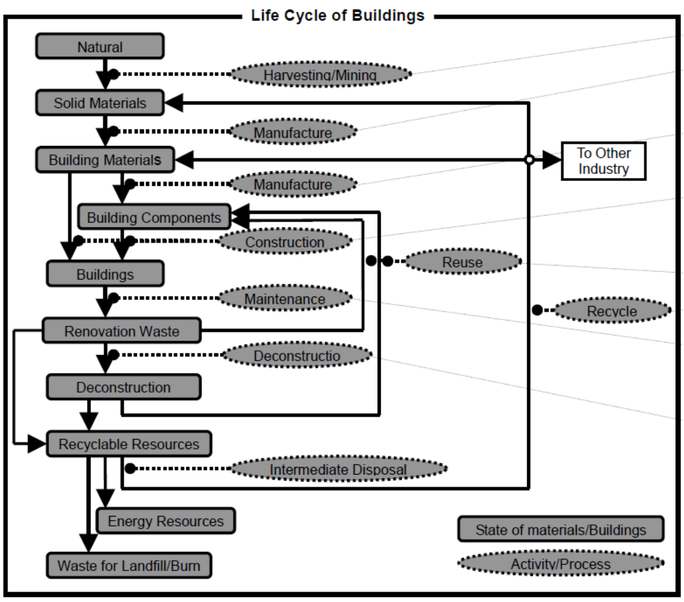

Figure 3: Life cycle of buildings[7]

[7] Chini R., A. Deconstruction and Materials Reuse: Technology, Economic, and Policy CIB Publication 266

2.2 End of life phase

End of life (EOL) refers to the final stages of a product or material's phase of use. The treatment and disposal of construction materials, once they have reached their end of life, is an increasingly important issue to minimise waste, carbon emissions and the use of landfill sites.

Usually, at the end of the lifecycle, building materials are dismantled and sent to landfills. This might indicate that the economic value of the building materials drops to zero. However, the end of a building's life does not necessarily lead to the end of the building materials' lifespans. Especially in the current situation of urban development, redevelopment and restructuring, large portions of erected building structures are demolished with spatial or functional, rather than structural or material, quality problems. For such a reason, at the point of demolition, a building, as an aggregation of building materials, is still functional. Therefore, either the whole building or the embodied building materials contain financial value that should not be neglected[8].

End-of-life covers that period of time and those processes which happen to a building's materials, such as timber, concrete and steel, when the building is deconstructed or demolished at the end of it useful, occupied life.

End-of-life is a distinct phase of the life cycle assessment process which is largely considered to '*complete the circle*' of a building's material's life cycle which most usually begins with extraction / sourcing of the raw material [but could be from re-cycling], followed by its processing, usage, maintenance and finally end-of-life.

2.2.1 End of life scenarios

EoL scenarios are based on current treatment technologies for the most common materials. They have to be defined depending on each national context, as scenarios are likely to vary nationally. Sensitivity analyses are possible to assess the impact of the future mix of waste treatment options. This aspect is likely to be predefined in every national EPD programme. It may be advisable to adopt rules from the national EPD programme that refer to the context of the product LCA study[9].

Standard end-of-life scenarios may be given within national building certification schemes or EPD programmes. For example, for Germany, one may refer to the DGNB scheme (e.g. criteria 1 to 5): predefined EoL scenarios for different classes of materials. Current practice should be used for developing the scenarios. Additional technical information, describing the technical conditions and characterizing the

[8] Kin Pun S. et al, Promoting the reuse and recycling of building demolition materials.
[9] EeBGuide Project. Operational Guidance for Life Cycle Assessment Studies of the Energy Efficient Buildings Initiative

product's technical and functional performance during the optional EoL life cycle stages, must be provided when a scenario is assessed. The default scenario should be based on actual achievement in current waste management practice, and not on what might happen in 50 years' time. It is important to use, as a reference for the evaluation, the average recovery rates based on the mix of recovery techniques, although additional scenarios can be used to illustrate the effect of the different waste management options that are available. The default scenario may vary according to the country of evaluation: for example, the same waste material may be more commonly landfilled in one Member State, used for energy recovery in another Member State, and recycled in another Member State. For each case, the percentage of end-of-life material typically going to various end-of-life options, such as landfill, incineration, energy recovery, recycling or reuse, should be estimated. This may be provided by the EPD programme, or may be available through national statistics or building-level schemes.

EoL scenarios can be provided for each EoL option. These may be useful if the product is sold in more than one Member State, as EoL options may differ significantly across Member States. Such scenarios also provide guidance on the most advantageous EoL option currently available. This is useful, for example, in determining the best way to dispose of construction waste arising.

Material-specific models for waste treatment may be relevant to take into account the emissions or the amount of energy recovery; otherwise generic models of inert waste in landfill or non-hazardous waste incineration can be used[10].

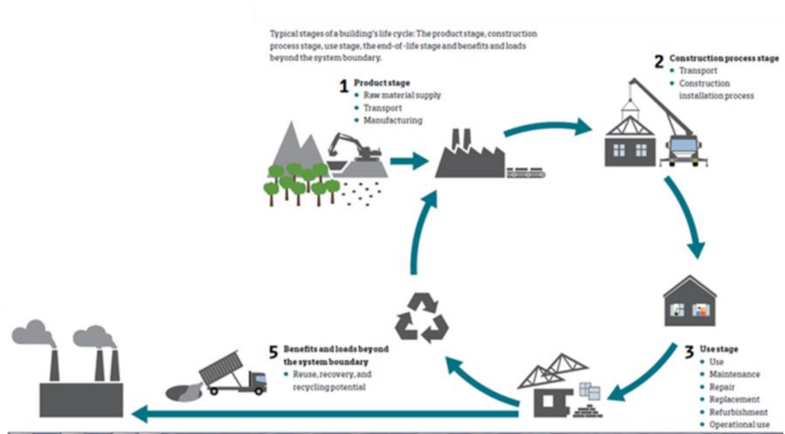

Figure 4: Typical life cycle for a building and which stages and processes are involved[11].

[10] EeBGuide Project. Operational Guidance for Life Cycle Assessment Studies of the Energy Efficient Buildings Initiative

[11] Danish Transport and Construction Agency. Introduction to LCA of Buildings.

As building technology is evolving constantly, demolition keeps developing in equipment and techniques. Currently, there are major demolition techniques that fall into three major categories, namely: mechanical demolition, deconstruction and implosion. Popular mechanical and implosive demolition techniques enable rapid and relatively simple demolition projects. However, these demolition projects yield enormous amount of building waste that is intermixed and contaminated, most of which end up as landfill. To divert waste from landfill, building deconstruction, which was the only available demolition techniques in ancient times, has been revived recently as a mechanism to eliminate waste disposal and promote waste reuse and recycling. In a deconstruction project, a building is carefully dismantled into its reusable components and materials. The processes of deconstruction are virtually the reverse of construction. Deconstruction is obviously a labour extensive and time consuming process, since large portions of the work needs to be undertaken manually. However, the environmental benefits of deconstruction are invaluable.[12]

Careful deconstruction, often a costly process, is most likely to lead to the possibility for the recovery of useful / re-useable materials, or at least partially intact components / building systems which can be re-used or re-cycled, for example, directly in the construction of other buildings.

Demolition is most likely to lead to a situation where some limited material may be recovered intact but much material / components will be damaged and broken. At this point, the base material may be recovered, through (further break-down and) sorting, to produce useable amounts of wood waste, such as wood pellets, steel for recycling or concrete for aggregate. Alternatively, rubble from the demolition process may be removed wholesale and placed in landfill.

The European Union Directive on waste obliges Member States to improve material recycling. The EU's objective is to achieve a recycling rate of 70% for construction waste by the year 2020. Re-use is one way to recycle and to achieve the objective[13].

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[12] Kin Pun S. et al. Promoting the reuse and recycling of building demolition materials.
[13] Talja A. VTT Technical Research Centre of Finland. Material efficiency and eco-efficiency. Re-use of structural elements Environmentally efficient recovery of building components.

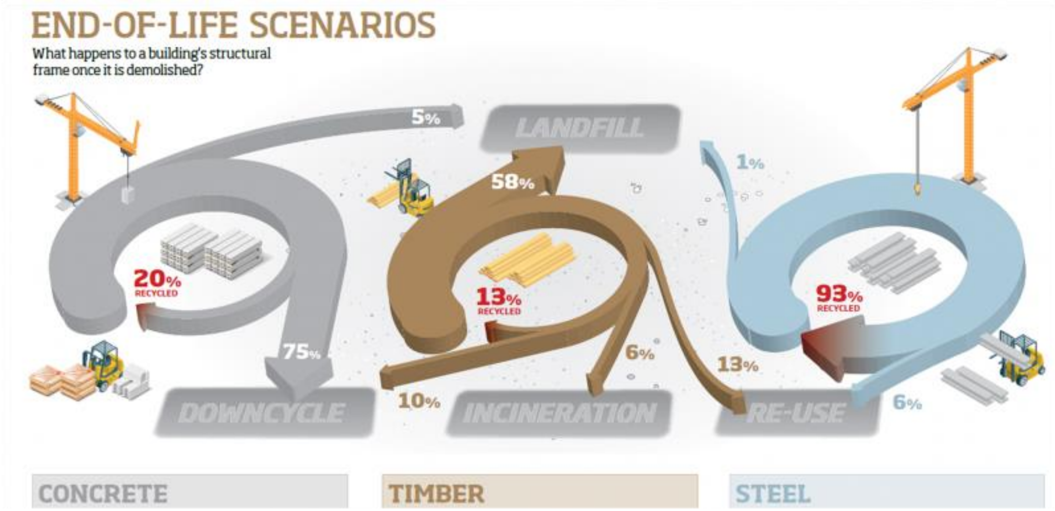

Figure 5: An example of end-of-life scenarios for concrete, timber and steel from Buildings[14].

Eco-efficiency stands for doing more – or the same – with less resources: using and re-using resources more efficiently throughout our economy. It is about eco-innovation: developing and using products, processes and other solutions that contribute to the efficient use of resources. It enhances resource productivity and generates more value from the use of resources. It means not wasting valuable materials.

To actually show the benefits of demolition waste reuse and recycling, the environmental impacts of a building demolition project need to be accurately quantified for the sake of comparison. Life Cycle Assessment (LCA) is currently a popular mechanism to evaluate the environmental impact of construction by figuring the total energy consumed during a product or a process. In LCA, the environmental effects associated with extracting, processing, manufacturing, transporting, using and disposing of products are regarded as embodied. In the building industry, the object often under investigation is embodied energy. Although the energy required to operate a building structure is much more substantial than the energy consumed in the construction activities, other embodied resources, including those spent prior to construction, are in fact significant to the environment, including material extraction and manufacturing. LCA captures all the relevant environmental effects with a product or process over its full lifecycle.[15]

[14] SteelConstruction.info. End of life options for pre-finished steel buildings.
[17] SteelConstruction.info. End of life options for pre-finished steel buildings.

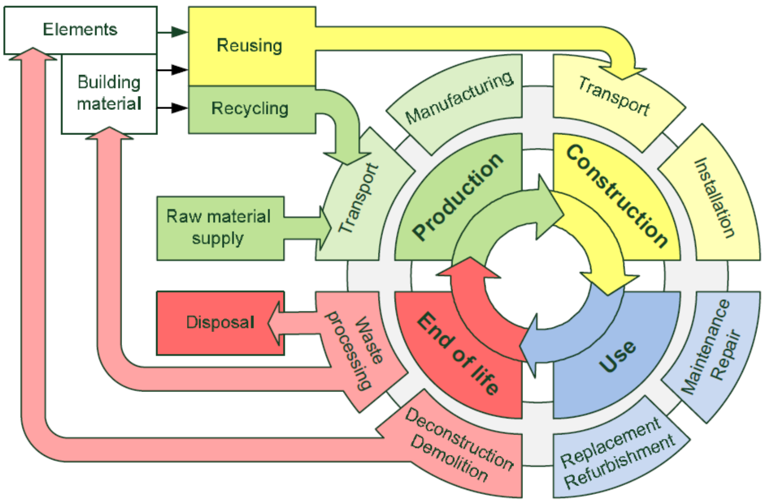

Figure 6: Structural elements life cycle[16]

Returning the structural components back to service in the built environment is a rather complex process affecting all the parties involved in the life cycle. Designers have to consider the new source of materials and carefully plan for deconstruction, increased demand for coordination and flexibility in decision making will be needed during construction, and finally new business areas can be opened up to provide services for the phase between deconstruction and new building.

The process depends strongly on the size and complexity of the element or structure that is being re-used. Five categories have been proposed from the smallest blocks (e.g. bricks and boards) to whole building frames.

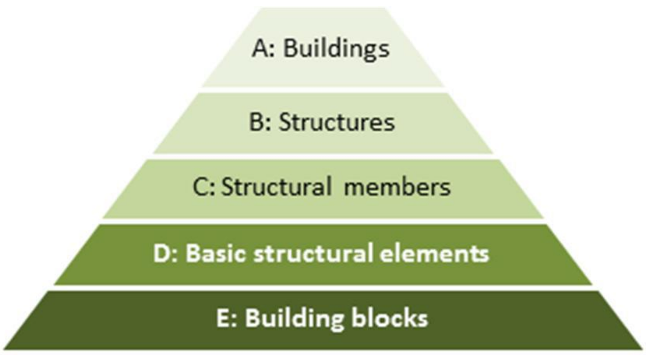

Figure 7: Categories of structural elements[16]

[16] Hradil P. et al., VTT Technical Research Centre of Finland. Re-use of structural Elements Environmentally efficient recovery of building components.

Building elements of a higher category can often be separated into several elements of a lower category. Even though the higher category element is typically more valuable than all its parts taken together, the separation would make sense, because it may be more difficult to find a suitable application of higher category elements.

All of the possible re-use scenarios will have different impacts on sustainability, meaning society, the environment and the economy together.

Re-use of building components is a rather complex process. Many different businesses interact over a long building life. Their effect on the whole re-use cycle is described in the following glossary and Figure 8.

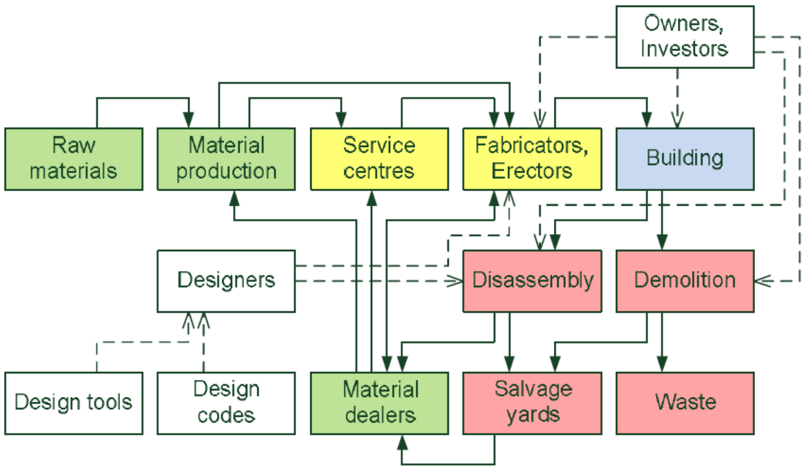

Figure 8: Major roles in the re-use process and their interaction[16]

According to the analysis carried out in the BAMB[17] Project, the built environment consists of a sequence of building phases (and sub phases) and a broad variety of actors. Only a few of these actors are involved in all phases (e.g. property owner), depending on the type of building project (e.g. public or private). Most actors, however, are only involved in one or two building phases and not throughout the entire value chain. It is observed that the design and build phases have relatively well established connections in terms of actors that are involved in both. However, as soon as the building is commissioned, these connections are cut off and actors that were involved in the design and building of the construction are rarely involved during use and repurposing/demolition phases. This means that a lot of valuable information about the construction, the operation, the materials and the reuse/recycling/recovery options is not available for the actors involved within

[17] BAMB Project. Key barriers and opportunities for Materials Passports and Reversible Building Design in the current system.

repurposing and demolition/deconstruction activities. Seen from the demolition/deconstruction side, this also means that building design and construction actors do seldom take into account the end-of-use or end-of-life consequences when making design or construction choices, leading to waste streams that cannot be recycled or only down-cycled. Moreover, if end-of-life issues would be taken into account during the design and construction phases, this would also facilitate the reuse of components, that are often worth much more than their constituent materials. In order to foster circularity in the building sector, connections between all phases in the value chain are necessary in order to support communication and information transfer across the whole of the value chain/network.

This is exactly what the BAMB project is aiming for. By supporting the development of Reversible Building Design Protocols, Materials Passports and related decision-making instruments during this innovation action project, "Design & Build" actors will have a better understanding on the potential consequences of their decisions made during these two crucial phases within the value chain. Moreover, the development of a Materials Passport IT Platform and a BIM prototype will serve as a proof-of-concept on exchanging information on building products and the building's operation to "Use and Repurpose" actors.[17]

3 End of life strategies

The end of life phase is a normal part of the life cycle of buildings. Without adequate cure, obsolescence will eventually result in the end of the service life, generally by demolition.

Exceptions are monuments and other structures with heritage or other intrinsic values that no one may demolish, and empty out of service structures on valueless land that no one will demolish. Even if obsolescence is defined as a condition that justifies demolition, there are other solutions like renovation, reuse and transformation to extend the service life of buildings. Apart from obsolescence, there can be many reasons to -or not to - demolish. To what degree these reasons become decisive motives depends on the interests and disposition rights and the capacities of the party involved. Despite an abundance of case studies and descriptions, empirical knowledge about the decision-making in the final phase of the life cycle of buildings and the underlying motives is scarce and fragmented. Data about demolition of non-residential property are generally not included in the statistics nor available from other resources. Knowledge about the decision-making in the final phase of the life cycle of buildings and the underlying motives is scarce and fragmented. It is generally regarded as a black box, in which a complex range of interrelated and often conflicting interests and expectations of different parties are blended with the interests, considerations and expectations of the proprietor, with the latter as decisive condition for the outcome. Following a more elaborated analysis of the decision process and underlying motives of proprietors, physical quality and market demand can be considered as the main decisive variables, with tenure and asset management as main conditional factors.[18]

3.1 Hierarchy of end-of-life strategies

The waste hierarchy is the legally binding guiding principle behind any waste management decision or system. The waste hierarchy is established in Article 4(1) of the EU Waste Framework Directive (2008/98/EC).

Generally, following this hierarchy should lead to the most resource-efficient and environmentally sound choice for the management of wastes. But this is not always the case. There are exceptions to the rule, and life cycle thinking and life cycle assessment are powerful tools to help identify where the hierarchy does not hold as well as to help compare options at any given level of the hierarchy.

[18] Thomsen A. Obsolescence and the end of life phase of buildings.

Figure 9: The waste hierarchy, as defined by the Waste Framework Directive (2008/98/EC)

3.1.1 Waste Prevention

The Waste Framework Directive defines waste prevention as: "*measures taken before a substance, material or product has become waste that reduce: (a) the quantity of waste, including* through *the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of harmful substances in materials and products* ". Prevention is often the best possible solution for the environment, as resources are not lost and the negative environmental impacts associated with waste management do not occur. Prevention (as defined in the Waste Framework Directive) also refers to measures taken to reduce the adverse impacts of generated waste on the environment and on human health, for example through minimising the content of harmful substances in materials and products. Opportunities for waste prevention occur across the life cycle of a construction or demolition project, not only at its end-of-life stage. The design stage, for example, offers many opportunities for reducing the environmental impact of both materials and waste, through the choice of materials and 'lean design' techniques. Waste prevention interventions can therefore range from simple actions on site, such as the introduction of plasterboard carriers to reduce breakage, to early design interventions, for example reducing the quantity of plasterboard needed in the fit-out stage.

• The Waste and Resources Action Programme (WRAP) Design Guide provides many ideas for waste prevention and other good management practices related to construction and demolition activities.

• The Building Research Establishment (BRE) has developed a True Cost of Waste Calculator which measures the environmental benefit of reducing wastage rates and materials consumption.

3.1.2 Preparing for re-use and re-use

Very simply, re-use means that a product, its components or entire building structures are used again for the same purpose, rather than being dismantled and sent for recycling, recovery or disposal. 'Preparing for re-use' means carrying out checking, cleaning or repair operations that enable waste materials to be re-used without any other pre-processing.

Very often, the benefits of re-use are straightforward, as re-use avoids the need for the manufacture of a new product. A simple example is the direct re-use of containers, bricks or other materials on site.

However, re-use can also mean:

• A separate collection and return system is required if the product is not reused by the same organisation;

• A cleaning or reconditioning stage is needed – for example following salvage of building components before demolition;

• More transport emissions occur – if the re-usable product is heavier or has a larger volume than the disposable one, or if re-conditioning infrastructure is limited and needs to be transported longer distances; and

• Compared to new and more efficient products, higher energy consumption may occur during the use phase, for example for electrical equipment requiring more energy.

3.1.3 Recycling

As the original, or 'primary', production of materials can require significant amounts of energy and raw materials (its 'embodied impact'), recycling into 'secondary' materials can be environmentally very beneficial. For example, separation of metals from C&D waste and recycling into other metal products has been shown to result in significant environmental savings[19]. EU waste policy aims to ensure that waste is used wherever possible as raw material to make new products. Recycling also saves energy: recycling an aluminium can, for example, saves around 95% of the energy needed to make a new one from raw material.[20]

The EU has set recycling targets for many types of waste, including old vehicles, electronic equipment, batteries and packaging, municipal waste and waste from construction and demolition activities.

Member States are working hard to put systems in place to ensure these targets are met. These systems include Extended Producer Responsibility, which makes

[19] European Commission Joint Research Centre Institute for Environment and Sustainability. A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA).
[20] European Commission Directorate-General Environment. Being wise with waste: the EU's approach to waste management

producers responsible for the entire life cycle of the products and packaging they produce, including the last stage of the product life cycle, when it becomes waste[20].

There are also considerable financial benefits, which already drive the recycling of many materials.

However, various factors can significantly influence the environmental comparison of recycling and alternative management options (e.g. energy recovery and disposal).

These include[19]:

- The distance to the reprocessing plant and the type of transport used;
- The energy intensity of the recycling process;
- Recycling efficiency (how much product is lost in the process);
- The quality of the secondary products; and
- The product(s) that the recycled material will replace.

3.1.4 Energy Recovery

An alternative to recovering the material value from a waste stream (i.e. recycling) is to recover the energy inherent within the waste material(s). This can lead to significant environmental benefits, particularly for materials with a high calorific content. Energy recovery includes any process that converts waste material into energy. Some non-recycling waste, which may contain higher energy value than coal, are able to be converted into energy, such as electricity, or alternative fuels like synthetic gas. Energy recovery technologies like waste-to-energy complement recycling and reduce waste that would otherwise be sent to landfills.

Non-recycling waste (end-of-life tyres; biomass, plastics …), however, are being transformed right now into alternative energy through advanced energy recovery technologies like waste-to-energy and plastics or tyres-to-oil. Waste-to-energy facilities produce clean, renewable energy in the form of electricity or heat, while plastics or tyres-to-oil transforms non-recycled plastic or tyres into a valuable commodity, creating a reliable source for alternative energy from an abundant, no-cost feedstock.

However, poor or incomplete burning of waste materials can result in environmental and health damage through the release of hazardous chemicals, including dioxins and acid gases. To ensure hazardous substances are completely destroyed, incineration plants need to burn waste under controlled conditions and at sufficiently high temperatures. Where the emissions of hazardous substances cannot be prevented, additional measures must be taken to reduce the releases into the environment. For these reasons, the European Union has set environmental standards for incineration and co-incineration plants. This legislation helps ensure that the environmental costs of waste incineration are minimized while the benefits are maximised. The legislation sets limit values for emissions from plants and requires these to be monitored. It also requires the recovery of any heat generated, as far as possible, and sets thresholds for the energy efficiency of municipal waste incinerators.

Energy recovery through incineration is often not the most efficient way of managing used materials, particularly those that are difficult to burn or which release chemicals at high temperatures. Member States are encouraged to use life-cycle thinking to weigh up the possible environmental benefits and drawbacks when deciding whether to incinerate waste[20].

3.1.5 Disposal

At the bottom of the waste hierarchy there are occasions where disposal of C&D wastes in landfill is unavoidable. There may also be occasions where this presents the best solution environmentally. Consider the case of low grade inert materials. To be recycled as aggregate, they may need to undergo further re-processing and transportation to a distant point of use. The impacts of doing so may be greater than both the 'avoided burdens' of producing primary aggregates and disposing of the inert waste material in a landfill. Life Cycle tools such as the WRAP aggregates model can help you to determine whether this is the case.

The hierarchy provides a simple tool to guide decision-making. There will be specific circumstances where the result suggested by the hierarchy might not apply, for instance where infrastructure or markets for recycled products are as yet undeveloped. In general, applying the "resource efficiency" principle will provide better environmental outcomes[19].

Table 1: Waste management hierarchy

Waste management hierarchy	Potential responses
1. Reduce	Includes building design and building life cycle assessment, design for deconstruction, adaptive reuse of existing buildings, use of new materials and technologies with increased reliance on recyclable building components
2. Reuse	Recovered construction and demolition waste particularly hardwoods, warehouse & wharf timbers, aluminium window & door frames, roof tiles, bricks, window glass, and other materials for resale should be segregated and on-sold to salvage yards. Direct re-use applications for non-segregated or unprocessed building waste is limited to site pre-loading or site contouring, or disposal to landfill which will be utilised after closure.
3. Recycle	Road bases and sub-grade materials, drainage medium, backfill material, civil construction, compacted hard stands, sealed and unsealed roads. Concrete aggregate and glass used in the manufacture of concrete kerbing or pedestrian pathways.
4. Disposal	Disposal in landfill for non-specific use.

Kibert and Chini write on the topic of deconstruction as a means to reducing the environmental burden of the built environment. They propose an explicit waste management hierarchy that includes the levels of landfill, burning, composting, recycling, reuse, and reduction. In this hierarchy the level of recycling is further broken down in to downcycling, recycling and upcycling, in which each is slightly more environmentally advantageous than the previous. The level of reuse is similarly broken into the reuse of materials and the more advantageous reuse of components or products.

In comparing the proposed end-of-life scenarios of the industrial designers with the architects, it can be seen that the subtle differences between product reuse, remanufacture, and repair may not be as relevant to the construction of the built environment as to product manufacturing (). If the building is considered as a product, then the vagaries of the sub-assemblies may be beyond the direct control and concern of the product (building) designer. It is appropriate then to combine product remanufacture and product repair, since both are concerned with the production of new' products. In this way it is possible to consider the technical results of the scenarios as a way of defining them[21].

Table 2: Levels of Hierarchy of End-of-life scenarios[21]

Reference	Young (1995)	Ayres (1996)	Graedel (1995)	Magrab (1997)	Fletcher (2000)	Guequierre (1999)	Kibert & Chini (2000)	Crowther (2000)
Most desirable					System level			Reuse building
↑	Reuse	Reuse		Reuse	Product level	Repair product	Reuse of product	Reuse product
	Maintain	Repair	Maintain		Product level	Repair product	Reuse of material	Reprocess material
End-of-life scenarios	Reman-ufacture	Reman-ufacture	Recycle component	Reman-ufacture	Product level	Repair product		Reprocess material
	Recycle	Recycle	Recycle material	Recycle	Material level	Recycle material	Recycle	Recycle material
↓							Compost	
Least desirable				Burning		Burning	Burning	
				Landfill		Landfill	Landfill	

There are four (differently scaled) possible technical results, which have been previously proposed by the author;

- the reuse of a whole building
- the production of a 'new' building
- the production of 'new' components
- the production of 'new' materials

These would relate to the four end-of-life scenarios of;

- building reuse or relocation
- component reuse or relocation in a new building
- material reuse in the manufacture of new component
- material recycling into new materials

[21] Crowther P., Developing an inclusive model for design for deconstruction. CIB Publication 266.

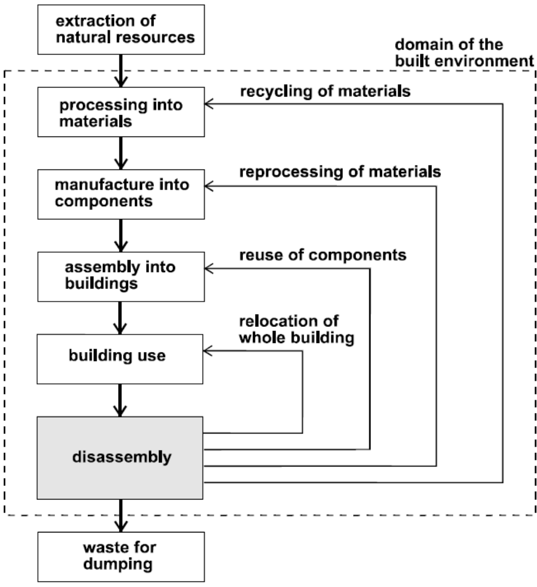

Figure 10: Possible End of life Scenarios for the built environment[21]

If the strategies of recycling as used in industrial ecology were applied to the built environment, the life cycle stage of demolition could be replaced with a stage of deconstruction. The typical once-through life cycle of materials in the built environment could then be altered to accommodate the possible end-of-life scenarios and produce a range of alternative life cycles.

3.2 EU Eco-Management and Audit Scheme (EMAS)

The EU Eco-Management and Audit Scheme (EMAS) is a premium management instrument developed by the European Commission for companies and other organisations to evaluate, report, and improve their environmental performance. EMAS is open to every type of organisation eager to improve its environmental performance. It spans all economic and service sectors and is applicable worldwide.

EMAS VERIFIED ENVIRONMENTAL MANAGEMENT | Performance, Credibility, Transparency

The eco-management and audit scheme (EMAS) is a scheme for voluntary participation by organisations committed to continuous environmental improvement. Within this framework, this SRD provides sector-specific guidance to the construction sector and points out a number of options for improvement as well as best practices.

Building end-of-life is considered in the *ANNEX Reference document on best environmental management practice, sector environmental performance indicators and benchmarks of excellence for the construction sector under Regulation (EC) No 1221/2009 on the voluntary participation by organisations in a Community eco-management and audit scheme (EMAS).*

This SRD is structured according to the different phases of the life cycle of a building (Table 2.1), from building design to the end-of-life of the building and from selection of the best environmentally friendly materials to waste treatment and recycling / reuse cycles. Not all the phases are covered in the same depth. The strategy to select the best environmental management practice in this document is based on the overall environmental impact during design, construction or renovation, the use phase and deconstruction activities.

Building end-of-life

This chapter is targeted at construction and deconstruction companies (NACE codes 41 and 43). It covers the best practices dealing with buildings having reached their end-of-life, with a focus on selective demolition of buildings with high material recovery rates.

Apply the waste hierarchy to end-of-life buildings

BEMP is to apply the waste hierarchy in the decision-making process concerning end-of-life buildings. With regard to the building as a whole, the priority is for the reuse of the end-of-life building, followed by the reclamation for reuse of materials, products and construction elements and finally the sorting of deconstruction and demolition waste streams for recycling.

Applicability

This BEMP is addressed to all construction and deconstruction companies, including SMEs.

Selection of environmentally friendly deconstruction/demolition techniques

BEMP is to use environmentally friendly deconstruction and demolition techniques, e.g. deconstructing and demolishing buildings selectively, maximising the amount of salvaged materials and the recyclability of the waste generated.

Building end-of-life

This chapter is targeted at construction and deconstruction companies (NACE codes 41 and 43). There are no considerable technical limitations to the applicability of this BEMP, although the extent to which selective deconstruction is possible depends on the previous building design.

Factors affecting the deconstruction process which may limit material recovery are:

- Safety, which may increase project costs;
- Time: deconstruction projects need more time than conventional demolition, so higher costs are expected;
- Quality and market acceptance: the cost of removing an element (e.g. a roof tile) should be compensated for by its price, while, at the same time, the reused element should be competitive and accepted by future users;
- Space: when there is a space limitation on a site, good planning is required; at the same time, some potential recycling processes may not be possible due to excessive time or higher costs (e.g. through intermediate storage);
- Location: the potential recovery of materials from a deconstruction project is subject to the availability of nearby recovery/recycling facilities;
- Weather: some techniques may require certain weather conditions that may not be coincident with project timing;
- Price fluctuations: for instance, scrap and other construction material recyclability depends in part on fluctuating market prices.

This BEMP is applicable to all construction and deconstruction companies, including SMEs, with a specialised profile in deconstruction and demolition projects.

Associated environmental performance indicators and benchmarks of excellence

Environmental performance indicators

(i46) Specific waste generation during the deconstruction phase, measured as weight or volume per unit of area or other representative factor (kg/m^2).

(i29) Percentage of waste diverted from landfill or incineration without energy recovery (%).

Benchmarks of excellence

(b12) Less than 5 % of material that can be reused or is recyclable is sent to landfill or incineration without energy recovery.

4 4RinUE end of life strategy

The 4RinEU End of Life Strategy aims to integrate the key issues highlighted on the "EU Construction & Demolition Waste Management Protocol"[23] and on other consulted bibliographic sources, such as the "Technical and Economic Study with regard to the Development of Specific Tools and/or Guidelines for Assessment of Construction and Demolition Waste Streams prior to Demolition or Renovation of Buildings and Infrastructures"[22]: the need for pre-demolition inventories, the waste management reporting, the final waste management report, the need for smart tools providing demolition process with reliable information on the valuable materials and subsequent reuse/recycling potential options in order to propose the best approach to the problem and possible ways to implement them.

Improved waste identification, separation and collection at source are at the start of the C&D waste management process. Improved waste identification requires clear and unambiguous definitions; it also requires good-quality pre-demolition audits and waste management plans to be prepared and executed. A crucial part of the source separation is the elimination of hazardous waste, as well as the separation of materials that hamper recycling, including fixation materials. Improved collection of goods for re-use and recycling requires selective demolition and appropriate on-site operations as well[23].

4.1 Definition of guidelines for quick identification and quantification of waste materials

A waste inventory performed prior to a demolition (or refurbishment) provides relevant information about the building and the contained C&DW. Qualities and quantities of the materials present in the building that will be set free along the process are identified, together with information about the location and form of the material. The identification includes information on the hazardousness of the materials (both due to the nature of the material or contaminations occurred during the use of the building).

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[22] Technical and Economic Study with regard to the Development of Specific Tools and/or Guidelines for Assessment of Construction and Demolition Waste Streams prior to Demolition or Renovation of Buildings and Infrastructures. Final Report.

[23] European Commission. Directorate-General for Internal market, Industry, Entrepreneurship and SMEs. EU Construction & Demolition Waste Management Protocol. September 2016.

By adding to this inventory recommendations on how these waste materials can be managed (reuse, recycling and other forms of material recovery, energy recovery or disposal), depending on legal requirements, (local) economics (e.g. value of recycled materials) and location (available (regional) infrastructure), a waste audit is produced. This will make it possible to generate a waste management plan (times, tasks & resources) and the corresponding budget[24].

After a review of extant literatures on existing DfD practices and tools, it became evident that none of the tools is Building Information Modelling (BIM) compliant and that BIM implementation has been ignored for end-of-life activities. Some of the benefits of BIM compliant tools include improved collaboration among stakeholders, visualisation of deconstruction process, identification of recoverable materials, deconstruction plan development, performance analysis and simulation of end-of-life alternatives, improved building lifecycle management, and interoperability with existing BIM software. The results provide the needed technological support for developing tools for BIM compliant DfD tools[25].

A BIM based tool for supporting pre-demolition studies has been developed in the framework of a European project called HISER[26] in which ACCIONA participated. The first functional version was internally launched in March 2017. Along the same year its use was demonstrated in several case studies around Europe with the participation of demolition companies, software developers, public bodies and RTD centers. The results are promising in terms of improving reliability and accuracy of materials quantification, facilitating the traceability of materials and quickening the evaluation of alternative demolition/recovery options.

Selective demolition should permit the recovery of a large volume of reusable and recyclable material unlike conventional demolition. It is therefore necessary to assess the attributed economic and environmental impact first. HISER project has developed a Building Information Modelling for Smart Demolition (BIM-SD) tool to support the collection and management of information of materials through smart processing of data in the pre-demolition stage. The software interface has been oriented to laptops and touch screen systems. It can be used in almost any portable device supporting WebGL. The expected benefits include improved reliability of

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[24] García D. et al. BIM for pre-demolition and refurbishment inventories and waste information management.

[25] Olugbenga O. Akinade.et el. BIM-based deconstruction tool: Towards essential functionalities. International Journal of Sustainable Built Environment

[26] HISER, 2015-2019. Holistic Innovative Solutions for an Efficient Recycling and Recovery of

Valuable Raw Materials from Complex Construction and Demolition Waste. European Commission, H2020-WASTE-2014. CN 642085.

calculation, easier traceability of materials and quicker evaluation of alternative demolition/recovery options.

This tool was demonstrated in several demolition projects through four case studies including a range of geographical situations and building typologies. For each project, the demolition planning is carried out by means of (a) traditional practices (e.g. inventory based on visual inspection, etc.) and (b) definition of BIM geometric model, identification and quantification of waste materials, data processing by means of the BIM-SD tool and automatic generation of waste management documents. After the execution of the selective demolition, time and cost for each alternative are compared.

4.1.1 Quick waste identification and quantification (waste management audit)

Pre-demolition audit or waste audit is the appropriate tool to assess the materials to be removed from the building or infrastructure and their potential value by external experts prior to the demolition or renovation activity. Such audits are essential since they enable all stakeholders involved to get information of the composition of waste and make it easier to find markets for different waste types. The development of guidelines for waste auditing is one of the action points of the Circular Economy agenda of the European Commission. It is likely that the Commission will recommend member states to make the waste audit mandatory in order to increase the quality of recycling. A framework for waste audit was developed in a contract work financed by Commissions' DG for Internal Market, Industry, Enterprises and SMEs (GROW). The guidelines are establishing the basic principles of waste auditing, identification, reporting and recommendations for the further treatment. This paper presents the basic needs and benefits of such harmonized approach to the waste auditing including good practices from the selected countries. It should be noted that the number of materials separated due to their dangerous nature is growing and the methods for the identification of contamination are better which can result in a slight decrease of recyclable materials, but in a better quality of the materials that are recycled.

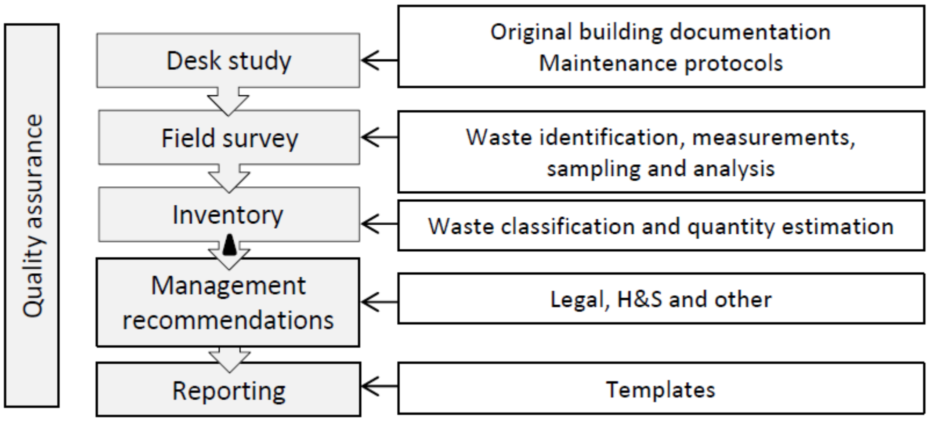

Figure 10: General scheme of the waste audit[27]

Relevance of waste audits

Performing a waste audit present a series of advantages (both economically and environmentally) providing important added value to the whole project. Special emphasis needs to be put on the following aspects about waste audits:

- Waste audits are the first step towards recycling.

- Waste audits promote fair competition amongst contractors (when performed before the call for tenders and included in the invitation).

- Waste audits increase awareness and ease traceability processes. It is of major importance to know the materials that will be set free (as especially the hazardous ones as unexpected costs during the works can be avoided).

- Environmental and technical quality of materials can be steered:

o Environmental aspects that will be improved include:

  - Which contaminants are present.
  - Contribute to the assurance that they are removed and do not end up in the environment.
  - The achievement of higher environmental quality of recyclable waste materials.
  - Technical quality aspects that will be improved include the identification of "higher quality" batches of recycled materials (for example concrete).

[27] DG GROW. Technical and Economic Study with regard to the Development of Specific Tools and/or Guidelines for Assessment of Construction and Demolition Waste Streams prior to Demolition or Renovation of Buildings and Infrastructures. Final Report.

Waste audits contribute to a better demolition waste management. Knowing the quantities and nature of materials expected leads to the optimisation of works (how many containers / on-site vs off-site sorting / etc.

The auditing process aims to deliver such documents that the owner can submit a demolition or renovation permit application and open a call for tenders. Furthermore, the outcome of the audit should also provide reliable estimates to contrast them with the results from waste management report.

The proposed methodology to carry out a waste audit includes the following stages:

- Desk study
- Site visit
- Inventory
- Management recommendations
- Reporting
- Quality checking.

The desk study and site visit should serve to collect all the information needed to perform the inventory and provide the waste management recommendations[28].

Quality Assessment of waste audits

Following the recommendations from the "Guidelines for the waste audits before demolition and renovation works of buildings"[29] the quality assessment of the waste audit should be based in two main aspects:

Auditor skills and certifications.

Auditors should meet a set of minimum requirements:

Skilled personnel. Auditors should show combine knowledge and experience. Experience provides an important background that can complement educative background and specific training.

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[28] DG GROW. Technical and Economic Study with regard to the Development of Specific Tools and/or Guidelines for Assessment of Construction and Demolition Waste Streams prior to Demolition or Renovation of Buildings and Infrastructures. Final Report.

[29] European Commission Directorate-General for Internal market, Industry, Entrepreneurship and SMEs. Guidelines for the waste audits before demolition and renovation works of buildings.

Adequate educative background and specific training. Auditors should have knowledge on construction, constructive systems, standardization, materials and hazardous substances.

Independence. Auditors and waste audits should be an independent process, so that the results obtained can be used by all the stakeholders involved in the process.

Traceability. Waste audits should be considered as living documents that are revised periodically. It is important to ascertain the quality of the audit performed and this should be done combining an initial verification with further verifications in several stages.

o Initial assessment during the waste audit.

o Verification after sorting. The quantities assessed during the waste audit should be checked against the materials obtained after sorting. Discrepancies found in the figures should be notified and justified.

o Verification with the management process. After reception at waste management facilities, the final figures of the materials received should be checked with the data predicted on the waste audit. Any discrepancy found should be notified and justified.

Institute of Civil Engineers (ICE) Demolition Protocol, 2008[30]

The ICE developed the Demolition Protocol in 2003 to have a robust methodology to assess the quantities of materials present in buildings and structures and their waste management options considering the waste hierarchy principle, when reaching the end of their lives. The Protocol has been updated, based on feedback received by stakeholders, and the updated version was published in 2008. It also provides an integrated approach to the development of Site Waste Management Plans. The pre-demolition audit is defined in the Demolition Protocol's methodology as; to enable construction and civil engineering projects to utilise all the demolition arisings, by setting reuse and recovery targets that should be met across a range of public and private sector projects.

4.1.2 Waste definition

Waste means any substance or object that the holder discards or is required to be discarded with the following exceptions: (a) uncontaminated soil and other naturally occurring material excavated in the course of construction activities where it is guaranteed that the material will be used for the purposes of construction in its natural state on the site from which it was excavated and (b) waste waters (such as trade effluent disposed of via tankers, foul sewers, surface water drains, water courses, etc.). Object is here the complete element or its part removed from the

[30] ICE, Institute of Civil Engineers, Demolition Protocol, 2008, ICE communications.

building or infrastructure during the demolition, deconstruction or renovation process, substance means the waste material that can be classified according to the European Waste Catalogue.

According to the EU Construction & Demolition Waste Management Protocol[31], Construction and Demolition waste is any waste generated in the activities of companies belonging to the construction sector and included in category 17 of the European List of Wastes. The category 17 provides for codes for several individual materials that can be collected separately from a construction or demolition site. It includes waste streams [hazardous and non-hazardous; inert, organic and inorganic] resulting from construction, renovation and demolition activities. C&D waste originates at sites where construction, renovation or demolition takes place. Construction waste contains several materials, often related to cut-offs or packaging waste. Demolition waste comprises all materials found in constructions. Renovation waste can contain both construction-related materials and demolition-related materials.

Hazardous waste is a waste that due to its (intrinsic) chemical -or other- properties poses a risk to the environment and/or human health. Waste listed as hazardous in the European List of Waste are marked with and asterisk in the List of Waste.

Waste holder means the waste producer or the natural or legal person who is in possession of the waste. The waste holder is the owner of the building or infrastructure, if not specified otherwise in the national legislation or the demolition/renovation contract. It is the duty of the waste holder to gain knowledge about the objects and substances intended for to discard and about their hazardous nature and contamination.

Waste producer means anyone whose activities produce waste. The waste producer is the person or legal entity that executes the demolition/renovation work.

European Waste Catalogue

2014/955/EU: Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council establishes a list of waste defined by six-digit code. The different types of wastes are divided into 20 chapters. The numbers of these chapters are the first two-digit numbers of the waste code.

Chapter 17 groups together "Construction and demolition wastes (including excavated soil from contaminated sites)", but some waste that can be found on a

[31] EU Construction & Demolition Waste Management Protocol

jobsite can be linked to other chapters. Anyway it is important to state that other sort of waste should be present in the building as furniture, fire safety equipment, etc. that has to be recorded in the waste audit.

The different types of waste that need to be identified, should fit in one of the following groups:

Inert waste - waste that does not undergo any significant physical, chemical or biological transformation. Inert waste will not affect other materials, even if they come into contact in any way likely to produce environmental pollution or harm to human health. Leachability and pollutant content of this waste need to be negligible.

Non-inert non-hazardous waste - This group of wastes can be divided into:

- Metals - In general metals are easily recyclable, but if they are polluted or there is a big mixture of metals, they may not be recyclable and could need to be landfilled.
- Wood - Wood should be further divided in untreated (clean) wood; wood treated without hazardous substances and wood treated with hazardous substances (which should be treated as hazardous materials)
- PVC - PVC can be mechanically recycled easily, but an appropriate sorting is key to optimize PVC recycling rates. Main types of PVC identified are: stiff PVC and soft PVC
- Plaster – Mainly represented by gypsum-based construction materials.
- Packaging materials - Packaging wastes are subject to specific regulation (Directive 94/62/EC and amendments)
- Mixed non-hazardous waste - has the same characteristics as household waste and can be treated by the same processes.

Hazardous waste - Hazardous waste was defined in Directive 2008/98/EC as that showing one or more of the hazardous properties listed in Annex III. Hazardous waste is subjected to specific precautions for their disposal, and is regulated all along Europe.

4.1.3 Material inventory

It is the duty of the waste holder to gain knowledge about the objects and substances intended to be discarded and their potential hazardous nature and contamination. The inventory of the waste materials and building elements is therefore the basic output of the waste audit requested by the waste holder and performed by the auditor.

Materials assessment, performed during the desk study and site visit, aims to present reliable data about the type and amounts of the demolition waste to be expected. In the inventory of materials and elements, materials assessment should be completed with the consideration of the ease of recovery of these materials. As regards buildings, it is advisable to provide in the inventory the materials assessment for each floor. In certain buildings like office buildings or hospitals the same elements reoccur in different rooms: in this case it can be sufficient to inventory one or two rooms in detail and for the others to register only deviations. All the necessary precautions not to extrapolate first impressions to the entire building need to be taken, for example performing systematic intermediate checking.

The materials assessment should include at least:

- The type of material to be classified as inert waste, non-inert, non-hazardous waste or hazardous waste, detailing the Eural code (from the European list of wastes) and description (since Eural code does not provide enough information);
- Quantification in tonnes, cubic meters and/or other relevant units of measurement.

Additional information can be required by the waste holder or building authority such as:

- An inventory of elements recommended for deconstruction and reuse. Materials of these elements should not be excluded from the waste inventory (exceptions may exist e.g. if the audit is part of the approved deconstruction plan);
- The location of the waste materials (and elements) in the building, in order to maximize the efficiency and safety of demolition or renovation.
- The quality of the material to assess the impurities that could be present. The fewer impurities in the waste fraction, the higher the value it can have.
- Its reusability in order to assess direct reusability of the material which depends on the nature of the material and material conditions.

4.1.4 Recommended templates for identification and inventory of materials

The following templates have been prepared following the recommendations from the technical and economic study prepared for DG Grow[32]:

[32] DG GROW. Technical and Economic Study with regard to the Development of Specific Tools and/or Guidelines for Assessment of Construction and Demolition Waste Streams prior to Demolition or Renovation of Buildings and Infrastructures. Final Report.

Figure 11: Recommended template for inventory of materials

BUILDING:

Level:

Other relevant information:

Construction unit:										
Building	**Type of material**	**Material identification**	**Waste code (EWC and EURAL)**	**Location**	**Quantity**	**Unit**	**Possible outlets[1]**	**Recommended outlet[2]**	**Precautions to take during the deconstruction phase[3]**	**Observations /Pictures and notes**
	Inert waste									
	Non-inert, non-hazardous waste									
	Hazardous waste									

[1] Reuse, recycle, backfill, energy recovery, elimination

[2] The recommended outlet must be identified taking into account the hierarchy of waste treatment and the potential possibilities in the proximity of the jobsite

[3] Example; do not leave the frame on the plasterboards, be careful to remove power plugs…

Figure 12: Recommended template for inventory of building element

BUILDING: **Level:** **Other relevant information:**

Construction unit:								
Element	**Units**	**Location**	**Reusable**	**Possible markets**	**Quantity**	**Materials identification and waste codes**	**Precautions to take during the deconstruction phase**	**Pictures and notes**

4.2 Definition of guidelines for waste minimization, re-use and recycling of components and materials (including evaluation of costs and benefits)

4.2.1 Guidelines for waste minimization

Waste management involves identifying potential waste streams, setting target recovery rates and managing the process to ensure that these targets are met.

Adopting the principals of good practice waste minimisation on a project can demonstrate a firm commitment to sustainable construction and environmental management. Good practice in waste management when are well implemented, bring a number of benefits. The main benefits include[33]:

- Reduced material and disposal costs – less waste generated means that a reduced quantity of materials will be purchased, and less waste taken to landfill will reduce gate fees for disposal. Cost savings will stimulate the adoption of improved recovery practices and motivate a sustained change in waste management practice;
- Increased competitive differentiation – benefits both developers and contractors, particularly where this will help to meet prospective client's sustainability objectives;
- Lower CO_2 emissions;
- Complementing other aspects of sustainable design; and
- Responding to and pre-empting public policy – those organisations responding to the thrust in public policy making for the increased sustainability of construction and the built environment will be in an advantageous position in comparison with those that wait until they are compelled to act by legislation.

With the implementation of good practice waste minimisation and management it is possible to be significantly more efficient in the use of natural resources without compromising cost, quality or construction programmes.

Fully benefiting from good practice waste minimisation and management on a project will mean adopting its principles at the earliest possible stage, preferably mandated by the client through procurement requirements. The principles of good practice should then be communicated and implemented by the design team, contractor, sub-contractors, and waste management contractors through all project phases – from outlines design to project completion.

[33] WRAP. Achieving good practice Waste Minimisation and Management. Guidance for construction clients, design teams and contractors.

The costs of waste are not limited to the cost of landfilling. The following costs should also be added[33]:

- The time taken by on-site sorting, handling and managing waste;
- Poor packing or overfilling of skips leading to double leading to double handling (this cost is very difficult to quantify); and
- The cost of material that have been wasted.

4.2.1.1 Implementing a waste minimisation hierarchy

The waste minimisation hierarchy is an important guide to managing waste. It encourages the adoption of options for managing waste in the following order of priority[34]:

- Waste should be prevented or reduced at source as far as possible;
- Where waste cannot be prevented, waste materials or products should be reused directly, or refurbished before reuse;
- Waste materials should then be recycled or reprocessed into a form that allows them to be reclaimed as a secondary raw material;
- Where useful secondary materials cannot be reclaimed, the energy content of waste should be recovered and used as a substitute for non-renewable energy resources; and
- Only if waste cannot be prevented, reclaimed or recovered, it should be disposed of into the environment by landfilling, and this should only be undertaken in a controlled manner.

Construction waste management should move increasingly towards the first of these options, using a framework governed by five key principles promoted by the European Union (EU):

- The proximity principle;
- Regional self sufficiency;
- The precautionary principle;
- The polluter pays; and
- Best practicable environmental option.

Clearly, the reuse of building elements should take priority over their recycling, wherever practicable, to help satisfy the first priority of waste prevention at source.

4.2.1.2 Avoiding waste at design stage

Avoiding generating waste in the first place is the best way to manage waste. Efficient, lightweight designs, which respond well to site characteristics, minimize not only waste, but also often result in cost savings in construction. Such buildings also often have

[34] Armanda Couto and João Pedro Couto. Guidelines to Improve Construction and Demolition Waste Management in Portugal. University of Minho. Portugal.

significantly lower long-term operating costs. Identifying potential waste early in the design process decreases waste generated during construction[34].

Recent research by WRAP[35] has identified the important contribution that designers can make in reducing waste is through design. WRAP has developed a number of exemplar case studies on live projects, working with design teams to identify and build the business case for action around designing out waste. This work has improved current understanding of how to reduce construction waste and has led to the development of **five key principles that design teams can use during the design process to reduce waste:**

1. Design for Reuse and Recovery
2. Design for Off Site Construction
3. Design for materials optimization
4. Design for Waste Efficient Procurement
5. Design for Deconstruction and Flexibility

Design for reuse and recovery - reuse of materials components and/or entire building has considerable potential to reduce the key environmental burdens (e.g. embodied energy, CO2, waste, etc) resulting from construction;

Design for off site construction - the benefits of off site factory production in the construction industry include the potential to considerably reduce waste especially when factory manufactured elements and components are used extensively;

Design for materials optimization – this principle draws on a number of "good practice" initiatives that designers should consider as part of the design process. Good practice in this context means adopting a design approach that focuses on materials resource efficiency (Figure 13) so that less material is used in the design (i.e. lean design), and/or less waste is produced in the construction process, without compromising the design concept. The Figure 13 shows in the grey boxes the areas where designers can have a significant impact;

Design for waste efficient procurement – designers have considerable influence on the construction process itself, both through specification as well as setting contractual targets, prior to the formal appointment of a contractor/constructor. Designers need to consider how work sequences affect the generation of construction waste and work with the contractor and other specialist subcontractors to understand and minimize these, often by setting clear contractual targets. Once work sequences that causes site waste are identified and understood, they can often be "designed out"; and

[35] WRAP. Designing out Waste: a design team guide for buildings

Design for deconstruction and flexibility- Given the importance of this principle, it is developed, in more depth, below.

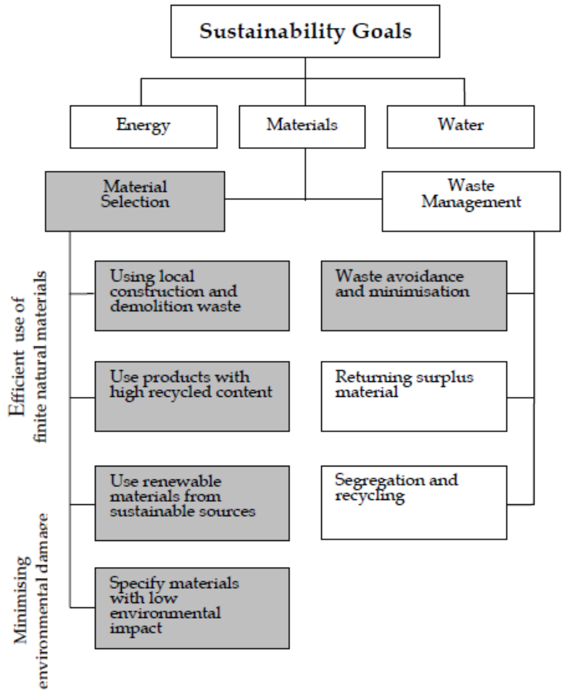

Figure 13: Materials resource efficiency as part of sustainable construction

4.2.1.3 Design for deconstruction (Dfd) and flexibility

Designers need to consider how materials can be recovered effectively during the life of building when maintenance and refurbishment is undertaken or when the building comes to the end of its life. Not to design with Design for Deconstruction and Flexibility in mind limits the future potential of Design for Reuse.

During the construction design stage there are several actions that could avoid waste generation, which may include:

• Designing to standard sizes, to modular and prefabricated construction, and requiring minimal earthwork;

• Incorporating recyclable, recycled and reusable products in construction;

DfD is practice to ease the deconstruction processes and procedures through planning and design. Deconstruction offers an alternative to traditional demolition that conserves raw materials and reduces landfill waste by considering buildings as untapped materials banks that provide provisions for the future. Similarly, design for disassembly also eases environmental burdens through key principles and strategies that facilitate end of-life recovery and reuse. Deconstruction is the process of demolishing a building but restore the use of the demolished materials. The deconstruction process essentially changes the traditional waste management process. The DfD process is an important strategy to conserve raw materials. The key principles of DfD include[36]:

1. Document materials and methods for deconstruction. As-built drawings, labeling of connections and materials, and a “deconstruction plan” in the specifications all contribute to efficient disassembly and deconstruction.

2. Select materials using the precautionary principle. Materials that are chosen with consideration for future impacts and that have high quality will retain value and/or be more feasible for reuse and recycling.

3. Design connections that are accessible. Visually, physically, and ergonomically accessible connections will increase efficiency and avoid requirements for expensive equipment or extensive environmental health and safety protections for workers.

4. Minimize or eliminate chemical connections. Binders, sealers and glues on, or in materials, make them difficult to separate and recycle, and increase the potential for negative human and ecological health impacts from their use.

5. Use bolted, screwed and nailed connections. Using standard and limited palettes of connectors will decrease tool needs, and time and effort to switch between them.

6. Separate mechanical, electrical and plumbing (MEP) systems. Disentangling MEP systems from the assemblies that host them makes it easier to separate components and materials for repair, replacement, reuse and recycling.

7. Design to the worker and labor of separation. Human- scale components or conversely attuning to ease of removal by standard mechanical equipment will decrease labor intensity and increase the ability to incorporate a variety of skill levels.

8. Simplicity of structure and form. Simple open-span structural systems, simple forms, and standard dimensional grids will allow for ease of construction and deconstruction in increments.

9. Interchangeability. Using materials and systems that exhibit principles of modularity, independence, and standardization will facilitate reuse.

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[36] Fernanda Cruz Riosa, Wai K. Chonga, David Graua., 2015. “Design For Disassembly and Deconstruction - Challenges and opportunities international Conference on Sustainable Design, Engineering and Construction A 1-9.

10. Safe deconstruction. Allowing for movement and safety of workers, equipment and site access, and ease of materials flow will make renovation and disassembly more economical and reduce risk.

4.2.1.3.1 Detailed DfD strategies:

- Use high-quality reused materials that encourage the markets for the reclamation of materials.
- Minimize the different types of materials which reduces the complexity and number of separation processes.
- Avoid toxic and hazardous materials that increase potential human and environmental health impacts, and potential future handling costs, liability risk and technical difficulties.
- Avoid composite materials, and make inseparable products from the same material that are then easier to recycle.
- Avoid secondary finishes to materials which may cover connections and materials, making it more difficult to find the connection points.
- Provide standard and permanent identification of materials chemistry.
- Minimize the number of different types of components to increase the quantities of similar recoverable components.
- Separate the structure from the cladding to allow for increased adaptability and separation of non-structural deconstruction from structural deconstruction.
- Provide adequate tolerances to allow for disassembly in order to minimize the need for destructive methods that will impact adjacent components.
- Minimize numbers of fasteners and connectors to increase speed of disassembly.
- Design joints and connectors to withstand repeated assembly and disassembly to allow for adaptation and for the connectors to be reused.
- Allow for parallel disassembly to decrease the time on-site in the disassembly process.
- Use a standard structural grid to allow for standard sizes of recoverable materials.
- Use prefabricated subassemblies which may be disassembled for reuse as modular units, or for efficient further separation off-site.
- Use lightweight materials and components that are more readily handled by human labor or smaller equipment.
- Identify point of disassembly permanently to reduce the time in planning the disassembly process.
- Provide spare parts and storage for them to allow for ease of adaptation and reuse of a whole component when only a sub-component part is damaged.
- Design foundations to allow for potential vertical expansions of the building in lieu of demolition.
- Use as wide of a structural grid as possible to maximize the non-structural wall elements.

- Consolidate mechanical, electrical and plumbing (MEP) systems into core units to minimize runs and hence unnecessary entanglement.

4.2.1.3.2 Identified barriers to Design for deconstruction

Despite the hype of the concepts of deconstruction and Design for Disassembly among the practitioners, it has yet achieved success in the industry due to its impracticality imposed by codes, standards and professional practices[37].

For example, building professionals will find it extremely challenging to integrate the concepts into their designs as they do not have the freedom and control over project schedule and cost, and they also face non-availability of materials. In order to successfully implement these concepts, there is a need to change the practices, perceptions and methods of delivery of different stakeholders. The market has to agree to develop and market these products, and the reuse/recycling market has to be matured enough to accept and sell these materials.

Several other variables can interfere with the decision making process on the use of the concepts of deconstruction and DfD. These variables can be related to project objectives (e.g., time, cost, expected results, quality, and safety) or to project conditions (e.g., project scope, market, hazardous materials, site accessibility, and resources).

Past studies pointed towards the design process as the main hindrance for deconstruction. Buildings are designed without considering the end of life and the process of recovery of these materials. Designers and builders, in general, have conceived their "creations" as being permanent and have not made provisions at the end of their lives. Most designers do not design with an end in mind. Chong et al[37] found that the designer was responsible for almost all of the obstacles in the recycling process. EPA (2008) stated that building materials and joints between components have become progressively complex which reduces the recyclability of salvaged materials.

If designers do not adopt a sustainable lifecycle approach, reuse and recycling activities will become unfeasible in the future. In addition, Chong et al[37] affirmed that designers would have to be at the frontline to ensure that salvaged materials will be reused. Those statements stressed the importance for Design for Disassembly.

Time constraint is another hindrance to deconstruction. The time required for disassembly may vary between three to eight times that of mechanical demolition. When time is a critical factor, deconstruction may not be a feasible alternative to demolition. According to Fernanda Cruz Riosa et al.[36] DfD techniques would reduce the time for deconstruction in several ways:

1) Establish a pre-planning phase prior to construction;

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[37] W.K. Chong, C. Hermreck, Understanding transportation energy and technical metabolism of construction waste recycling, 2009.

2) Require the proper related documents (plan, inventory, as-built) that ease the deconstruction and the materials recovery processes;

3) Provide training to the construct ion team and helping to increase their productivity;

4) Require all construction materials to be labelled; and

5) Avoid the use of hazardous materials that consume an extra time during demolition/deconstruction process.

Costs may also be a hindrance to deconstruction. There is a common perception that cost pertaining to deconstruction is greater than demolition and disposal. However, studies had shown that it is not always true. According to Fernanda Cruz Riosa et al.[36] the variables that influence costs include:

1) Material storage prior to final destination;

2) Higher labor costs;

3) Higher costs with workers insurance;

4) Transportation of debris;

5) Removal of hazardous materials;

6) Training expenses;

7) Local and regional market and demand for used materials;

8) Materials' conditions; and

9) Landfill fees.

There are also variables that could reduce cost. They include:

1) Resales value;

2) Partnerships among public, private and non-profit organizations that can help to raise funding and share benefits;

3) Financial incentives provided by governments; and

4) Savings related to the use of equipment, since in deconstruction activities the only large mechanical equipment often needed is the forklift.

The DfD helps to identify market for salvaged construction materials and this increases the resale values. On-site sales can be an alternative to reducing transportation and storage costs. Labor and insurance costs are usually greater for deconstruction, but they can be counterbalanced by saving from equipment use. By avoiding hazardous materials, DfD eliminates the costs pertaining to their removal. In addition, proper training can improve the salvage methods to conserve the quality and conditions of the materials. The Government could act to increase the values of salvaged materials, and reduce landfills' area to increase landfill cost, high disposal fees encourage the use of deconstruction, reusing and recycling. Investing in information and education, and also for recycling facilities and legislations are some of the approaches that could potentially make construction recycling and subsequently deconstruction more affordable.

Other common challenges faced by deconstruction are contractual issues. Normally, demolition contracts do not require the materials reuse or recycle, but clauses can be added to address and incentive those practices. Additional time and planning are needed to enhance the contract. As each project is unique, the contractual terms and clauses would have to be developed according to the projects' unique conditions and addressing all issues related to the particular project. The DfD's planning phase requires additional time to develop a comprehensive contractual terms that cover the guidelines of a deconstruction plan.

Manufacturers' lack of involvement and responsibility to minimize waste is another challenge to be overcome. It is part of the designer's role to demand manufacturers' involvement and responsibility (e.g., requiring data about the products composition and reusing/recycling methods). Finally, there is a lack of accounting methods for measuring benefits of deconstruction and the recyclability of materials and buildings. The lack of appropriate methods causes recycling process to be oversimplified and its costs and benefits cannot be measured in an efficient way[36].

Consistent quantitative studies are still lacking in the deconstruction field. By studying successful cases of DfD, it may be possible to collect enough data to determine recyclability metric. This metric will help the designer's and owner's decision making to new projects, and hopefully improve the cost-effectiveness of deconstruction. It can also increase and measure deconstruction's environmental positive impacts[36].

4.2.2 Guidelines for Reusing waste

Hobbs and Adams[38], at BRE, worked with other partners to identify best practices across the EU, which included increasing the level of reuse. The results from evaluating Member States policies, practices, performance and stakeholder viewpoints were used to develop a series of recommendations. In terms of reuse, these recommendations included:

- Mandatory pre-demolition and renovation audits with promotion of reuse – as currently in place in Hungary & Finland. Ideally, these would be undertaken by an independent party and the actual performance (in terms of levels of reuse) compared to the suggested levels of reuse proposed in the audit.
- Managing supply and demand – where products and materials cannot be used again on the same site, there should be mechanisms to match supply and demand (linked to clear traceability to promote best use options). This could be through stockholding facilities, such as reclamation yards, and material exchanges/reuse platforms, which directly connect those with surplus materials/products to those who might want them.
- Innovation in reuse – some of the issues preventing reuse, such as time consuming manual labour needed to separate products, can be alleviating through new

[38] Hobbs, G., Adams K., (BRE). Reuse of building products and materials – barriers and opportunities. As part of the BAMB project (www.bamb2020.eu).

technologies. For example, the REBRICK10 mechanical brick cleaning system in Denmark.

- Support for the reclamation sector – both in terms of R&D and business support. There are new start-ups and longstanding enterprises in this space, though the demand for the 'reclaimed aesthetic' can lead to the stocking of reproduction items, which should be discouraged.
- Construction product declaration and recertification to address a key barrier to reuse. This is challenging in existing buildings where the data link to the past, in terms of manufacturing information, are often severed through periods of multiple ownership and management.
- Better impact data – especially in the context of life cycle assessment. There is currently little distinction between reuse and recycle in calculating impacts, although this is under review in a number of projects, including BAMB, Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste (HISER) and FISSAC.
- Data management, including BIM, could be improved and manipulated to give much better understanding of the reuse potential of new developments, prior to construction. This could facilitate a much better end of life outcome in terms of future reuse. This is a key outcome from the BAMB project, which is also looking to adapt to existing buildings to influence refurbishment options.

Full advantage should be taken of all opportunities for the reuse of construction materials. The inclusion of period architectural features salvaged from old buildings can greatly enhance the aesthetics and appeal of new construction. Excavated soil can also be used creatively in the landscaping of developments and for the construction of embankments and screening/noise abatement berms in civil engineering projects.

Reusing building materials prevents environmental impacts by reducing the need for virgin natural resources to be mined and harvested, while saving forests and natural areas from further degradation. Reusing waste is efficient, as it does not require further processing, thereby not requiring further energy use. Efficiency can be improved further by reusing materials on site, eliminating the need for transportation. There are several opportunities for waste reuse as following is described[39]:

- Careful demolition can maximize the reuse value of materials, particularly fittings, floorings and timber linings;
- Sort demolition materials and identify the materials that can be reused, and grade accordingly to quality and re-usability;
- Reuse rock, soil and vegetation on site for landscaping;

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[39] Armanda Couto and Joao Pedro Couto. Guidelines to Improve Construction and Demolition Waste Management in Portugal.

- Stockpile the materials for removal and reuse off site, ensuring adequate provision for sediment and erosion control (ensuring minimal impact to the aesthetic quality of the surrounding environment);
- Reuse materials from the demolition stage;
- Buy used materials from reclamation yards where possible re-usable shuttering materials with eventual wreck value should be preferred even if investment costs are higher;
- Re-usable shuttering materials with eventual wreck value should be preferred even if investment costs are higher; and
- Waste selection. Residue must be stored in segregated containers, according to the material origin of the material; wood, metal, packages, aggregates, etc.[43]

According to Gilli Hobbs and Katherine Adams[40], from BRE, there are a number of challenges affecting reuse. Depending on national and local circumstances, these can include:

- Mismatch of supply and demand – both in terms of quantity and quality. If heavy materials need to be moved long distances to reach their markets, this can increase costs and environmental impact significantly.
- Insufficient time allowed for deconstruction and careful packing of reusable items – the length of time needed to deconstruct can be unappealing where extra costs are incurred through having a building (such as local property taxes) or loss of revenue on a replacement building owing to an extended scheduling of works. There can also be a time constraint linked to planning permission expiration.
- Lack of facilities locally – some countries, such as the UK, have a good spread of reclamation facilities, although space is limited and expensive in highly built up areas.
- This can cause a disparity between the location of the stocks of reclaimed items and the market for such items. The third party costs will need to be added to the purchase price, which can diminish the attractiveness of reclaimed products compared to new. This is particularly key when matched against possible risks associated with reuse.
- Reluctance to use products without certification of tested performance is one of the biggest barriers to reuse, particularly in a structural capacity. Often there is very little information on where the product has come from and its length of use in a particular application. This means that the 'worst case scenario' is normally applied to the potential reuse applications. Testing of performance can be expensive and require destruction of samples to mitigate possible risks of further use. These costs will be added to the cost of the product/material and may override savings from reuse.

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[40] Hobbs, G., Adams K., (BRE). Reuse of building products and materials – barriers and opportunities. As part of the BAMB project (www.bamb2020.eu).

- Health and safety risks of manual deconstruction are considered to be a key reason for the move to mechanical demolition techniques. Whilst these risks can be mitigated through improved data on the building design and composition, such information is often not available.
- Building technology is a mixture of traditional and rapidly changing techniques. Both can cause challenges in further reuse, such as cement mortar used in brick and block construction, through to rapid fix, prefabricated panelized systems which are multimaterial composites.
- Value of products and materials can be an opportunity or a barrier. In case of low value/cheap products and materials, the incentive to reuse versus the cost of careful removal can be low or negative.
- In summary, there are multiple and inter-related reasons for the fall in reuse, making it inevitable. The main challenge is to consider how to overcome these barriers in the forthcoming and existing built environment.

4.2.3 Disposing of waste

Disposal of waste should be considered a last resort, for materials that cannot be reused or recycled in the region. Unsorted loads may incur in a disposal penalty at landfills.

Hazardous materials need to be disposed of correctly

The waste management on site may include the following:

- Recommended waste diversion of each of the waste streams identified (reuse, recycling, backfilling, energy recovery and elimination) and estimation of the diversion rates. Different alternatives can be provided if there are some that represent similar advantages;
- Recommended on-site sorting activities that may include the description of the installation requirements for storage, handling, separation and for any other operation to manage the different sources of materials;
- Valorisation of the materials and deconstructed building elements assessed in the previous phase;
- Estimated cost of waste management process can be extracted from previous information after consulting different waste management facilities.
- Recommendations regarding possible precautions to take during the deconstruction phase or the waste management phase must also be done.

4.2.4 Waste management plan definition

Whilst the pre-demolition audit focuses on the products (‘what’), a process-oriented waste management plan (‘how’) is to be prepared if any material from construction, renovation or demolition operations is to be re-used or recycled. A good waste management plan contains information about how the different steps of the demolition will be performed, by whom they will be performed, which materials will be collected selectively at source, where and how they will be transported, what will be the recycling, re-use or final treatment and how to follow up. Such a plan also covers how to address safety and security issues, as well as how to limit environmental impacts, including leaching and dust. In the plan it should be stated how both the non-hazardous and hazardous waste will be managed.

It is crucial that demolition activities are carried out according to a plan. After the demolition, the contractor should make an overview about what has really been collected at source and to where the waste materials have been transported (for re-use, for pre-treatment (sorting), for recycling, for incineration, landfilling). This information should be (1) checked with what was foreseen in the inventory, and (2) provided to the authorities.

It is recommended that this whole process is supervised by a local authority or by an independent third party, for example by an external waste management organisation through:

- An “inter-demolition” control at site by a third party, after removal of the hazardous waste;
- After the fact: on the basis of sampling controls carried out by the same independent third party who has prepared the pre-demolition audit
- After the fact: a desk control to check what happened with all of the non-recyclable or non-reusable materials (a check of transportation documents, certificates of treatment or waste processing, etc.).

4.2.5 Identification of key factors affecting recovery of materials

Factors affecting recovery of materials in the demolition process:

The extent to which materials may be recovered effectively in the demolition process depends on a range of factors, including the following ones:

- Safety, which may increase project costs;
- Time. Selective demolition needs more time than traditional demolition, so higher costs are expected. Optimal solutions regarding potential recyclability and re-use should be considered.
- Economic feasibility and market acceptance. The cost of removing an element (e.g. a roof tile) should be compensated for by its price, while, at the same time, the re-used element should be competitive and accepted by future users. For some materials, e.g. iron/metal/scrap, market prices fluctuate strongly depending also on seasonality.
- Space. When there is a space limitation on a site, separation of materials collected should take place in a sorting facility. Space limits specifically require good planning.
- Location. The number of recycling facilities in the surroundings of the project site or the local supply waste management services may limit the potential recovery of materials from a deconstruction project.

- Weather. Some techniques may be dependent on certain weather conditions that may not coincide with project timing.

4.2.6 Guidelines to improve source separation

A key aspect of proper waste management is to keep materials separated. The better inert C&D waste is separated, the more effective recycling will be and the higher the quality of recycled aggregates and materials. However, the degree of separation depends strongly on the options available at the site (e.g. space and labour) and on the costs and revenues of separated materials. Such separation can be challenging: buildings have become increasingly complex and this has implications for demolition works. Furthermore, over the last few decades, an increasing amount of materials have been glued and the use of composite materials has extended as well.

When starting C&D waste recycling, one typically starts with the easiest materials for which secondary markets already exist. In many cases this will be the inert fraction, but in some Member States it can also be metals or wood. However, every situation is different.

A distinction needs to be made between the materials with a view of their treatment options, such as:

- cleaning for re-use (for example soil);
- re-use (for ex. structural steel, metal sheet and tiles);
- recycling in the same application (for ex. metals, paper, glass, cardboard and asphalt);
- recycling in another application (for ex. aggregates, wood for particleboard manufacturing);
- incineration (for ex. wood, plastics, paper packaging);
- disposal (for ex. hazardous waste).

Source separation involves the following types of operation:

- hazardous waste separation;
- deconstruction (dismantling including separation of side streams and fixation materials);
- separation of fixation materials, and;
- structural or mechanical demolition.

4.2.7 Hazardous waste separation

Proper decontamination needs to be done for a number of reasons other than reuse or recycling: to protect the environment; to protect the health of workers; to protect the health of people living in the surroundings of the site, and for safety reasons. Typical hazardous waste products from construction, renovation or demolition works are asbestos, tar, radioactive waste, PCBs, lead, electrical components containing mercury, insulation materials containing hazardous substances etc.

Decontamination is necessary so that hazardous particles will not contaminate the recyclable materials. Even if it is present in a very small proportion of the total waste materials, the possible presence of hazardous waste materials can reduce markets' confidence in the recycled waste materials drastically and therefore the perceived quality of the recycled products.

Hazardous waste therefore needs to be removed correctly and systematically prior to demolition as it can be 'explosive', 'oxidising', 'toxic', 'harmful', 'corrosive', 'irritating', 'carcinogenic' or 'infectious'. The waste management plan needs to foresee which actions are to be taken if unexpected hazardous waste materials are found.

Throughout the process, hazardous waste removal needs to comply with existing (national) level legislation. Depending on the Member State, the treatment of some of these waste types (e.g. asbestos) is regulated, whilst this is less so for others (e.g. PCB's and PAH's).

4.2.8 Selective demolition or dismantling

Main waste streams, including inert waste from buildings or civil infrastructures should be treated separately (e.g. concrete, bricks, masonry, tiles and ceramics). For the use of recycled materials in high grade applications, a more selective demolition can be required (such as separate collection/dismantling of the concrete and masonry).

An increasingly wide range of materials need to be considered for (manual) dismantling, to enable re-use, including techniques such as stripping (before demolition) and scavenging (after demolition). Examples include glass, marble fireplaces, precious woods such as walnut and oak, traditional sanitary ware, central heating boilers, water heaters, radiators, window frames, lamps and lamp-frames, steel structures, and cladding materials. Other materials which are to be considered for re-use or recycling include gypsum, insulation foam, concrete, and mineral wool and glass wool. Such operations allow for subsequent re-use and recycling of the materials themselves, but also aim at the purification of the main stream (i.e. inert waste destined for the production of recycled aggregates). Side-streams including fixation materials, like gypsum, can therefore compromise the quality of the C&D recycled material. Side-streams risk not being treated properly if there is no local/national regulation in place.

4.2.9 Guidelines to improve waste collection

Improved waste identification, separation and collection at source are at the start of the C&D waste management process. Improved waste identification requires clear and unambiguous definitions; it also requires good-quality pre-demolition audits and waste management plans to be prepared and executed. A crucial part of the source separation is the elimination of hazardous waste, as well as the separation of materials that hamper recycling, including fixation materials. Improved collection of goods for re-use and recycling requires selective demolition and appropriate on-site operations as well.

Clear and unambiguous definitions are a crucial starting point and it is important to pay proper attention to the exact use of wording. The field of C&D waste management is fraught with different terms and concepts, due to the large variety of perspectives and stakeholders involved. As C&D waste management is primarily a local activity, strong differences in terminology exist between Member States as well. Annex A provides an overview of the definitions and terms used in the Protocol.

4.2.10 Guidelines to improve waste logistics

Transparency needs to be assured throughout all phases of the C&D waste management process. Traceability is important for building confidence in the products and processes and to mitigate any negative environmental impacts.

Proper management of C&D waste still presents a problem in the EU, and data on its treatment is partly missing. Therefore, it is necessary to strengthen record keeping and traceability mechanisms through the establishment of electronic registries especially for hazardous C&D waste in the Member States. Good practices already exist in this domain in some Member States.

Registration of C&D waste constitutes a vital step for tracking and traceability and in order to register waste, it is necessary to know what types of C&D waste are expected. Therefore, a pre- demolition audit is of high importance. But equally important is to check afterwards that the waste has been processed according to plan, and that rules and regulations for the handling of these waste streams have been enforced.

When registering C&D waste it is recommended to use the European List of Waste in order to assure compatibility of data across the European Union.

Try to keep distances short. Proximity of sorting and recycling plants is very important for C&D waste, which in case of bulky materials such as aggregates for construction (asphalt, concrete, etc.) cannot be transported by road over longer distances (usually maximum 35 km). Unless transported in large volumes by rail or waterway, longer distances are simply not economically attractive, while environmental benefits of recycling diminish over longer distances as well.

Optimise the use of road networks and profit from appropriate information technology (IT). For example, tailor-made software exist that allows driving directions to be optimised for minimum fuel consumption.

Where possible, use waste transfer stations (or collecting boxes) – they play an important role in the local waste management system, serving as the link between a local C&D waste collection point (a demolition site) and a final waste disposal facility. Facility sizes, ownership, and services offered vary significantly between transfer stations. Nevertheless, they all serve the same basic purpose: consolidate waste from multiple collection points. Occasionally, transfer stations also provide waste sorting and recycling services. It is important to assure traceability of C&D materials also in the case of waste transfer stations.

Guarantee the integrity of the materials from dismantling to recycling. For example, in the case of glass recycling, the degree of cleanliness of the containers is crucial. This requires the necessary attention by the logistic organisation – such as the use of multi-use containers. As soon as glass comes into contact with concrete, stone or brick residues, it is no more suitable for recycling in a circular mode (re-melting).

Tracimat is an example of a non-profit, independent demolition management organization recognized by the Belgian public authorities that issue a "certificate of selective demolition" for a specific C&D material that has been collected selectively at the demolition site and subsequently gone through a tracing system. The demolition certificate shows the processor whether the C&D material can be accepted as "low environmental risk material" which means that the purchaser (recycling plant) can be quite sure that the C&D material meets the quality standards for processing at the recycling plant. Therefore the “low environmental risk material” can be processed separately from ”the high environmental risk material”.

4.3 Identification of best available technologies for recovery construction materials

The literature study towards re-use and high quality recycling technologies of the three largest C&D waste streams, stony materials, metals and wood, shows that there are several technologies available for this purpose. Therefore, the barriers seems to be in other parts of the system. By means of a qualitative research, the stakeholders in the C&D waste recycling system were asked for their opinion on the current C&D waste recycling system and their view towards future recycling of building materials. In general, the stakeholders concur that sorting of the materials, the economical climate and the type of building materials are the main bottlenecks that withhold high quality recycling.[41]

4.3.1 Guidelines for waste processing and treatment options following the waste hierarchy, resource efficiency, sustainability and cost savings.

Following the waste hierarchy offers wide-reaching benefits in terms of resource efficiency, sustainability and cost savings. A wide range of waste processing and treatment options exist, and these are commonly known as preparation for re-use, recycling and material and energy recovery – in that order of priority. The actual choice of the waste management option differs from case to case, depending on regulatory requirements, as well as economic, environmental, technical, public health and other considerations.

Non-inert materials and products need to be sorted depending on their economic value. Metal has an established resale value, and there is significant demand for materials such as bricks and tiles as well.

[41] Mulders L., Master thesis. High quality recycling of construction and demolition waste in the Netherlands.

However, many materials need to be processed or treated on the basis of primarily environmental criteria. Hazardous waste always needs to be separated and disposed of according to the national regulations on hazardous waste.

Hazardous waste should not be mixed with non-hazardous waste. Some types of C&D waste are not hazardous in their original form, but during the demolition stage can become hazardous through their mixing, processing or disposal. They can also pollute non-hazardous materials and thus make them non-reusable/recyclable. A classic example is lead-based paint thrown onto a pile of bricks and concrete, turning the whole pile into hazardous waste.

4.3.2 Preparation for reuse

According to the EU Construction & Demolition Waste Management Protocol[42], preparing for re-use is to be promoted as it involves application with little or no processing. In theory, re-use offers even greater environmental advantages than recycling since environmental impacts associated with reprocessing do not arise. However, in practice this may not be easy always.

Element-reuse is the third option of the Delft ladder. As pointed out earlier, element-reuse is possible after dismantling a building designed for dismantling. But what is going to happen with all the existing buildings? Can they be dismantled into useful elements? The question arises in what way, and in which order, a building should be dismantled which was never meant to be dismantled? Dismantling a building into elements and components is a way to keep the building materials in their own cycle for as long as possible. The main advantage of this approach is that buildings will not be downgraded to secondary raw materials or building waste but into reusable elements and components. This results in more positive effects than just reducing the building waste.

Other results are:

- Less use of raw materials which leads to less reduction of the landscape;
- Less use of energy which leads to a lower greenhouse effect and less acidification;
- Building materials will remain in their own cycle for as long as possible.

Dismantling a building is easier said than done, especially when it has not been built with the intention of regaining the used elements and components. The first thing to do is to establish the building method and the matching details. With this information in hand and the knowledge of dismantling techniques you can determine the success of disassembling the building into elements or components If there is no dismantling technique currently available for a certain detail, a new technique could be developed. This new technique will only be developed if it can be economically applied[43].

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[42] EU Construction & Demolition Waste Management Protocol.
[43] J. Kristinsson, Ch. F. Hendriks, T. Kowalczyk. Reuse of secondary elements: utopia or reality. Delft University of Technology, Faculty of Architecture.

One of the greatest bottlenecks, as mentioned above, is that most existing buildings were never meant to be dismantled into reusable elements or components. This means that the thoughts about the building method and details used were only concerned with how the building was to be put together, and not how it could be dismantled. A reinforced concrete structure where every joint is poured together is hard to dismantle. A possible technique could be by sawing the construction. A disadvantage of this method is that the reinforcing steel will be exposed to the air, which could lead to the 'decay' of concrete.

For demolishing a building a contractor can choose from a range of methods, such as: balling, impact breakers, hydraulic shears, explosives, gas expansion and solid expansion. They all result in breaking the building into smaller pieces, but not into reusable elements or components. For dismantling a building, methods have to be found which don't damage the element or component and which will lead to a successful reuse of the element or component. Potentially applicable methods are mechanical cutting and grinding, thermal cutting water jet cutting and laser cutting. These methods make a cut of a width of a few millimetres to a centimetre at most, which is acceptable[45].

Concrete reuse

Concrete can be re-used in various ways in its original form. An example is to leave the concrete structure in place while modernising the inside space or façade/curtain wall of the building.

Figure 14: Reused concrete in different applications

Another option is the re-use of specific concrete elements with little processing: pre-fabricated elements and concrete blocks are cut in smaller elements and cleaned of mortar. This requires the careful and therefore time-consuming dismantling of the building to avoid damaging the elements and the transportation to the other construction site.

4.3.3 Bricks, tiles and ceramic reuse

Extracting roof tiles and storing them for re-use is not difficult and bricks that are left over from building projects can also be diverted to other uses among which the incorporation into new buildings: for example, a new architectural trend in Berlin is to reuse facing bricks in new buildings. To do that, building deconstruction is imperatively required.

Figure 15: Reused bricks and tiles

Figure 16: Reused ceramics

However, these materials are often contaminated which raises several issues: Cleaning bricks is time consuming, difficult and dusty work that, if mechanized, is apparently rarely successful. Cement rich mortars are difficult to remove. In countries like Greece, where mortar from ancient constructions is a full ceramic material, it does not need to be removed. Excess mortar dust can inhibit the adhesion between mortar and bricks and lead to weaker masonry, depending on the mortar composition. Bricks may vary in quality. It is therefore difficult to assess the strength and load-bearing capacity of masonry made from recycled bricks. European and national standards are very strict and it is extremely difficult to be sure that re-used bricks used in new structures will be durable. Due to the difficult nature and high labour costs associated with the process, the use of re-used bricks may be more expensive than the use of new bricks.

4.3.4 Wood reuse

Wood from buildings reaching their end of life can be directly re-used when proper deconstruction methods have been implemented. This could be encouraged by the increasing market demand for large dimensions building pieces.

Figure 17: Reused wood framing and panels

Components for reuse (timber)

- Framing: Solid/structural (finger jointed KVH), glued and glue laminated timber
- Panels: cross-laminated timber (CLT) or light frames
- Joists Laminated or composite members usually fitted with endjoints.
- Roof girders: More complex structural systems
- Old growth timber is a valuable material and will usually justify the time required for a more delicate removal process. Timbers are generally sold through timber brokers to be cleaned and resold for timber framing, or as feedstock for high quality architectural millwork.
- Some species of dimensional lumber can also be quite valuable. Wood framed buildings can be partially or totally deconstructed. While this is often a more labor intensive approach, cost avoidance and the value of the materials can offset initial cost.

Figure 18: Reused wooden panels

4.3.5 Recycling

Sound planning of construction activities and related waste management activities on construction sites are a prerequisite for high recycling rates and high-quality recycling products. Much of C&D waste is recycled for economic reasons, however recycling of materials such as concrete, wood, glass, gypsum drywall and asphalt shingles has benefits well beyond financial one's: it results in greater job creation, reduced use of primary materials and reduced landfilling. Avoidance of landfilling also supports environmental protection, a smarter use of natural resources, energy savings, a net decrease in greenhouse gas emissions and avoidance of excavations in (or exploitation of) rural/forest regions[45].

Materials can either be recycled on-site into new construction resources or off-site at a recycling plant.

Typical materials recycled from building sites include metal, lumber, asphalt, pavement (from parking lots), concrete and other stony materials, ceramics (e.g. bricks, roof-tiles), roofing materials, corrugated cardboard and wallboard.

Figure 19: Typical materials recycled from building sites

C&D waste recycling needs to be promoted particularly in densely populated areas, where supply and demand are geographically close, resulting in shorter transport distances than for the supply of primary materials, such as in the case of aggregates[45].

Recycling facilities are not always located within the vicinity of the construction sites. The transportation of the salvaged materials for reuse and recycling would consume additional energy, time and money, and thus make the process less environmentally and economically friendly. The new market created by the advancement in deconstruction will provide opportunities for more recycling facilities. It will consequently shorten the distances between the recycling facilities and the construction sites. One of the steps for a successful DfD is to identify the market opportunities to determine the feasibility of deconstruction for a specific site. Deconstruction is currently more common in the metropolitan areas due to the constant demand for building materials and a large number of deteriorated properties[44].

The lack of information and education is one of the major obstacles to materials recycling. The designer's role is essential in the education of the general public and stakeholders on deconstruction and recycling, and active marketing could be used as an approach to enhance the community education and awareness on these strategies and their benefits.

[44] Cruz Rios, Fernanda & Chong, Wai & Grau, David. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. Procedia Engineering. 118. 1296-1304. 10.1016/j.proeng.2015.08.485.

In addition, quantity and size of building materials, jointing methods that do not ease disassembly and complexity of materials' composition are common challenges pertaining to existing design. Designing new buildings following the DfD principles can overcome the barriers to recycling. DfD requires standard size components, mechanical joint methods (instead of gluing or welding) and materials with simpler compositions that facilitate recycling and reusing processes.

Finally, there are stakeholders-related challenges, such as the lack of experience with recycling methods, inability to identify market for debris, resistance to change, contract formats, and lack of communication between the team. By requiring a deconstruction plan and a complete inventory of construction materials, DfD would improve the ability to developing markets for salvaged materials. The detailed planning phase demanded by this design process would facilitate communication of the reuse and recycling of salvaged materials[45].

The waste diversion potential in a demolition scenario is considerable. The building's construction type and project schedule are the two primary factors in determining what and how salvage, reuse, and/or recycling can be accomplished. Consider the following:

- Develop the project schedule to accommodate salvage, reuse, or recycling. The quality and quantity of materials salvaged is a direct function to the time available for salvage.
- Prior to demolition, salvage as much useable material and components as the schedule will allow. Windows and doors, wood flooring, cabinetry, architectural millwork, electrical fixtures, plumbing fixtures, mechanical equipment ... anything that can be detached and removed ... can be usually be salvaged and reused. When developing the C&D Waste Management Plan, identify the most accessible and valuable materials, thereby optimizing the application of resources to this task.
- Concrete and masonry materials can be recycled to produce aggregate. This may be accomplished on-site with mobile equipment, or rubble can be hauled to a permanent recycling facility. Preferences vary among demolition contractors and recyclers about whether the building should be gutted prior to demolition, leaving only concrete and reinforcing to be crushed, or demolished intact, and the debris sorted as part of the concrete crushing process. Consider how the recycled concrete aggregate (RCA) will be used, what RCA products are most useable, and how the rubble should be processed to produce these products. If aggregate materials are required for the project, on-site recycling can provide these materials at a reduced net cost.
- Landscape materials and wood that is not painted with lead-based paint, treated with an arsenic-based preservative, or otherwise contaminated with a hazardous or toxic material can be shredded into mulch, composted, or chipped for boiler fuel. This can be accomplished on-site or off-site. If mulch or compost is required for the project, shredding on-site can provide these materials at a reduced net cost.
- Structural steel and metals are almost universally recycled. This should be standard practice with any demolition contractor.

- If none of the alternative salvage, reuse, or recycling options are possible, mixed demolition debris can be hauled to a C&D debris recycling facility, as described above.

The following information has been extracted from the report "Service contract on management of construction and demolition waste"[45] European Commission (DG ENV). This study on C&D waste represents a useful tool for the definition of the future steps and trends regarding the management of this waste stream in Europe.

4.3.6 Concrete recycling

Concrete can be reprocessed into coarse or fine aggregates.

The first step is to remove all impurities such as insulation and steel reinforcement before crushing and grading. As a consequence, an effective sorting out at the construction site or at the treatment facility is essential to maximise the recycling potential. Mobile sorters and crushers are often installed on construction sites to allow on-site processing. In other situations, specific processing sites are established. Sometimes machines incorporate air knives to remove lighter materials such as wood, joint sealants and plastics. Magnet and mechanical processes are used to extract steel, which is then recycled.

Figure 20: Concrete reprocessed into coarse or fine aggregates

Once sorted and processed, these aggregates can be used as such in road works, or reintroduced into the manufacturing of concrete. These different possible applications are described below.

Coarse aggregates can be used for road base, sub-base and civil engineering applications. Finnish research has found that recycled concrete specified to an agreed quality and composition in the sub-base and base layers can allow the thickness of these layers to be reduced due to the good bearing properties of the material. Indeed, for such an application the unbound cementitious material present in recycled aggregates has proved superior behaviour than virgin aggregates such that the strength is improved providing a very good construction base for new pavements.

[45] European Commission (DG ENV). Service contract on management of construction and demolition waste – SR1. Final Report Task 2

Therefore, the use road construction sector represents one of the main applications for recycled concrete aggregates and can significantly contribute to reaching the 70% target (the demand of recycled aggregates for road construction could already buffer up to 75% of the concrete waste generated).

Coarse aggregates can also be used as a filling material in quarries (referred to as backfilling) which is in practice especially in Eastern Europe whereas in Western Europe quarries are rehabilitated into leisure spaces. Crushed concrete can also be used in earthwork constructions, to build streets, yards and parking areas, as backfilling for pipe excavations, environmental construction, foundations for buildings, etc.

Fine aggregates can also be obtained from concrete waste and used in place of natural sand in mortars. However, the use of recycled concrete fine aggregates could affect directly the mortar content and therefore its workability, strength and can cause shrinkage due to high water absorption. This could increase the risk of settlement and dry shrinkage cracking. For these reasons, recycled fine aggregates are not used in the production of structural concrete. Moreover, the contamination of concrete with gypsum may hinder the recyclability of the material, as cleaning represents important additional costs, both economical and environmental.

The above applications are often referred to as “down-cycling” as opposed to reintroducing recycled concrete directly into concrete production, where it can be used as a substitute to natural aggregates. Both coarse and fine recycled aggregates can be used in concrete production. However, as cement is not recyclable, this option still requires the consumption of virgin cement. Technically, the use of recycled aggregated in the production of concrete is limited for structural reasons. A study by the National Ready Mixed Concrete Association (NRMCA) in the US has concluded that up to 10% recycled concrete aggregate is suitable as a substitute for virgin aggregates for most concrete applications. UK research indicates that up to 20% of total aggregates may be replaced by good quality crushed concrete. Under these conditions, recycled concrete can be used for most common concrete applications. Actual practices vary greatly; for example, countries like the UK and the Netherlands already achieve a recycled concrete content of 20%, whereas this application is almost non-existing in other countries such as Spain.

4.3.6.1 Economic impacts of concrete recovery

Despite the environmental benefits of recycling concrete, its limited production costs do not encourage re-use and recycling. Nevertheless, using recycled concrete can also show economical advantages, depending on the local situation. The identified factors include: Proximity and quantity of available natural aggregates Reliability of supply, quality and quantity of C&D waste (availability of materials and capacity of recycling facility) Government procurement incentives Standards and regulations requiring different treatment for recycled aggregate compared to primary material Taxes and levies on natural aggregates and on landfill

Recycled concrete aggregates in Europe can sell for 3 to 12 € per tonne with a production cost of 2.5 to 10 € per tonne. The higher selling prices are obtained on sites where all C&D

waste is reclaimed and maximum sorting is achieved, there is strong consumer demand, lack of natural alternatives and supportive regulatory regimes[46].

4.3.7 Bricks, tiles and ceramic recycling

A high proportion of ceramic C&D waste is well suited to being crushed and recycled as a substitute for newly quarried (primary) aggregates in certain lower grade applications such as engineering fill and road sub-base.

Figure 21: Clay bricks from demolition waste

The different recycling options promoted by the European Tiles and Bricks Association are described below:

- To fill and stabilize minor roads, especially in wet areas such as woods and fields. The practice is common in countries that lack adequate stone supplies such as Denmark. The material is generally crushed.
- Crushed clay bricks, roof tiles and other masonry can be used on a larger road building projects, especially as unbound base material. In Germany, the maximum brick content for such use is 30%, due to the quality requirements for frost attacks and impact resistance. The material replaces natural materials, such as sand and gravel, which are normally used in large amounts for this purpose.
- Aggregates for in situ. Crushed clay bricks and other masonry can also be used to level and fill pipe trenches. The fine crushed material will replace natural materials such as sand.
- Crushed clay bricks, tiles and other masonry can also be used as aggregate in concrete. The crushed material replaces other raw materials such as sand. This is commonly practiced in Austria, Denmark, Switzerland and especially the Netherlands.
- Tennis sand produced by crushing red bricks and roof tiles. The fine surface layer is laid over courser-grained layers that can comprise crushed clay brick matter. The

[46] European Commission (DG ENV). Service contract on management of construction and demolition waste – SR1. Final Report Task 2

process is most efficient when it occurs at brick or tile factories where there is an abundance of scrap material.

- Crushed bricks and tiles can also be used as plant substrates. The material may be mixed with composted organic materials and is especially suited for green roofs: the porosity of the material allowing retaining water plants can rely on during dry periods.
- Encourage proper segregation of the bricks and tile waste that you generate. Assign an appropriate area for stacking and storage of reclaimed bricks and tiles, and assign a skip for collection of cement or mortar waste. Use simple labels on all skips and at all storage areas, detailing what is, and isn't allowed in each;
- Segregated bricks and tiles that you cannot re-use could be offered to other projects or organisations.
- Alternatively, waste bricks and tiles can be sent to be recycled into aggregate either on- or off-site.

4.3.7.1 Economic impacts of the recovery of bricks, tiles and ceramic

The harnessed extraction of clay and the development of new manufacturing techniques maintain clay bricks and tiles as competitive building materials that have good quality, long life, minimal maintenance requirements and provide energy efficient solution during the use phase. The reduced costs of bricks, tiles and ceramics produced from raw materials are therefore not encouraging the development of recycling. The above mentioned number of SMEs would also decrease the chances for developments in recycling (heavy financial burden to SMEs while relatively small financial gains - if any -) except with the development of specific recycling facilities covering larger areas in a MS[45].

4.3.8 Wood recycling

In the past few years, the wood recycling has known improvements along with the development of companies dedicated to this activity. C&D wood waste can be remanufactured into high added-value products such as medium density particle boards or fibre boards or even wooden plastic that can contain a high proportion of recycled materials.

Figure 22: Wood waste

This application is by far the main application for recycled wood.

The particle board production in the EU-27 is estimated to be around 30 million[45] m^3. 1m^3 of particle boards necessitating 0.65 tonnes of wood on average, 19.5 million tonnes of wood are needed each year to sustain the European production of particle boards. The share of post-consumer recycled wood input into this production shows high geographical differences (from 20% in France to 80% in Italy), and is estimated to reach 24% on average (5 million tonnes). This represents 25% to 50% of the C&D waste wood generated in Europe. This estimation is in line with the average EU-27 recycling rate of 31% proposed by the JRC.

Other forms of recovery of non-contaminated wood waste include: Landscaping, where recycled wood can be used as decorative mulches, surface material for pathways, or impact absorbing playground surfaces Equestrian surfaces, for both indoor and outdoor arenas Animal bedding products.

The extent of such applications in the EU is currently unknown. However, WRAP's study shows that the production of animal bedding and equines surfaces is the third most important end user industry of recycled wood.

Figure 23: Recycled wood in landscaping applications

- Wood can be reclaimed from many demolition, refurbishment and subsequent new build sources, including floorboards, rafters, doors, frames, offcuts, temporary works, fencing, posts, poles and railway sleepers. It can be re-used directly or sent to recycling depots for cleaning, de-nailing and resizing or being turned into chipboard;
- Segregate wood from the waste stream and, where possible, re-use it in its original form. Encourage segregation by setting aside an appropriate dry storage area on-site for timber to be stacked and stored. Ensure that skips for timber waste are easy to access and well labelled (use simple signs such as 'Timber skip, no masonry'). Assign a skip for segregating unusable wood waste;
- Identify likely sources of the various waste wood types and volumes you are generating – consider which materials you can re-use onsite, and which are

returnable to the supplier (e.g. blue CHEP pallets should always be re-used or returned); and

- Wood treated with some chemicals or preservatives can be hazardous wastes and must not be mixed with untreated wood.

4.3.8.1 Economic impacts of wood recovery

Due to the competition of utilisation and the limited supplies, the market price for recycled wood is going up. The margin of the market price is influenced by the following elements: The regionally available amount of waste wood. The intensity of the competition between material and energy recovery Seasonal variations (winter stock etc.)

In Germany for example, prices for waste wood differ not only depending on the type of wood but also between regions. Therefore, average prices only give some orientations. For highly contaminated waste wood, the distributor even has to face additional costs for proper disposal and/or special treatment[45].

4.3.9 Gypsum recycling

The collected plasterboard stream has to undergo several steps in the recycling process. First, paper layers of the plasterboards are removed as much as possible, then gypsum is crushed into powder and eventually this powder is sent back to plasterboard manufacturers so that they can make new plasterboards from it.

The gypsum powder is estimated to represent 94% of the total plasterboard waste collected. The remaining 6% refer to paper and cardboard (and the related contaminants) composing plasterboards and can be re-used in various ways such as composting (as very little gypsum is left on the paper) or heat generation.

There is always a residual paper fraction that remains in the powder and which hinders the improvement of the introduction rates of recycled powder into the processes that are currently in place. The associated risks are the damage of the manufacture machinery and an effect on the acoustic or thermal quality of the final product.

Figure 24: Gypsum waste

According to Eurogypsum, between 5 and 10% of gypsum powder resulting from construction plasterboard waste is re-integrated in the closed-loop system. This figure is a European average and huge differences exist between MS. Indeed, recycling practices exist in Denmark, Germany and other Northern European countries while recycling is limited in Greece and Spain or is not applied at all in Eastern Europe countries. In some MS where comprehensive gypsum recycling schemes have been established (e.g. Denmark) overall recycling rates of 65% can be achieved.

This discrepancy is due to specific national legislation, to mentality aspects and especially to the existence of a market that would encourage the economic activity associated to recycling.

- Plasterboard recycling processes can handle demolition waste, waste from rebuilds, production scrap in the form of virgin plasterboard offcuts, complete or broken board parts;
- Provide a dedicated skip for plasterboard collection. Cover the skip, as dry plasterboard is much easier and more cost-effective to reprocess. Ensure each skip is easy to access and well labelled (use simple signs such as ‘Plasterboard Only’);
- Minor contamination is acceptable from certain materials (e.g. nails and screws, wallpaper and other wall coverings) but you should avoid excessive contamination as it reduces the cost effectiveness of the recycling process; and
- Plasterboard is a ‘non-inert’ waste. It should be disposed of separately from inert waste such as bricks and concrete to prevent contamination of these wastes.

Emerging techniques:

Only a small quantity of gypsum demolition waste is currently recycled due to challenges surrounding contamination with other materials. This is therefore an area of continuing research and development to improve the manufacturing process by making possible the re-introduction of gypsum with a higher residual paper fraction (therefore a gypsum powder with a higher impurity rate) or enhancing the techniques for the removal of paper from plasterboards.

Other options are considered to partially or fully replace virgin gypsum that is usually used for cement manufacture and for agriculture. They are described below.

- Recycling as a raw material in the manufacture of cement

A small percentage of gypsum is usually incorporated into cement in order to modify its setting characteristics and traditionally the gypsum additive was obtained by mining. Gypsum waste could substitute virgin gypsum though WRAP (Waste & Resources Action Programme) has identified significant actual and perceived barriers to the incorporation of recycled gypsum from plasterboard waste into cement mixtures.

A study was then undertaken for WRAP to determine how the barriers could be overcome and how the cement industry could maximise the amount of gypsum waste utilised in its products and hence diverted from landfill.

The study has demonstrated through desk studies and practical trials that recycled gypsum, of the quality currently available, can substitute technically for mined gypsum in the production of bagged cements, but that it remains to be proven acceptable to the ready mix market.

- Recycling as a soil treatment for agricultural benefit

Gypsum is traditionally added to agricultural arable soils to improve soil condition. For this purpose, gypsum is usually mined or quarried, which depletes natural resources among other impacts. A study was undertaken by WRAP to evaluate whether recycled gypsum produced from waste plasterboard is effective as a soil treatment in commercial potato production. A parallel study with winter wheat was carried out in early 2008. Both studies were undertaken by the research and development department of Velcourt Ltd.

The main effect on soil condition by adding gypsum are considered to be improved structure, leading to improved drainage, water-holding capacity, aid restoration of calcium and sulphur deficiencies and improve the efficiency of a plant's uptake of inorganic nitrogen fertiliser.

Trials were realised and led to the conclusion that applying recycled gypsum to land used for potato production was beneficial in its effects on the soil and the quality of the crop. The farmer involved in the trial was convinced of the benefits of recycled gypsum and intends to continue its use on his fields when required.

However, farmers have indicated that the complications of applying for an environmental permit for the use of gypsum waste deter them from using cheaper, but equally beneficial gypsum from waste plasterboard.

However, this recovery technique might have important impacts on ground water sulphides concentration.

4.3.10 Metals recycling

Metals are the most monetary valuable materials in the C&D waste. There is a large number of different metals that can be distinguished. The division made by the LoW is containing the following categories: ferrous metal and steel, copper, bronze and brass, aluminium, lead, zinc, tin, mixed metals, contaminated metals and cables. Some applications of metal: copper, zinc and lead are used in the building industry in facades and roofs. Copper is also used for tubes. Steel is used for making the construction of the building more firm and in reinforced concrete. Even though the LoW distinguishes six different types of non-ferrous metals, the metals were grouped into ferrous metals, non-ferrous metals and cables in this research. This is a result of different aggregation levels in the data used for the MFA.

Figure 25: Metals from demolition waste

4.3.11 Plastics recycling

- There may be several different types of plastics in your demolition waste, including PVC in windows and gutters, HDPE in drainage pipes and fittings, PP in tarps and crates and LDPE in plastic film packaging and damp-proof membranes;
- Check with your waste contractor to find out if they have any specific requirements (e.g. what are the acceptable levels of contamination) for the separation of different plastics, and whether there are financial incentives (e.g. reduced skip prices) to make this worthwhile. Note that plastic can usually be collected in one skip for mixed plastics (which may also include packaging);
- Clearly label the plastics skip and detail what it should contain to prevent contamination;
- If you have plastic crates or pallets your supplier may offer a bring-back scheme whereby you can send the packaging back to the manufacturer for re-use, so store them separately from other waste plastic; and
- Sometimes plastic piping sections can be re-used on the job, saving on the costs of new materials. Consider which other reclaimed plastics can also be re-used on your project.

4.3.12 Glass recycling

Most of the glass on building sites comes from window waste. The glass used for this is called flat glass;

Figure 26: Flat glass from demolition waste

- Consider whether flat glass separation is relevant for your project. If not, are other glass wastes likely to occur (e.g. catering, containers etc) and can these be collected easily? (e.g. positioning dedicated wheelie bins next to canteen exits). If this is a particular problem, you may wish to specify targets for the catering operation separately from the construction workforce;
- For demolition projects, when deconstructing windows, safely remove the glass from the frames and store each material separately.
- When handling glass all personnel should wear steel toe cap boots at all times.

4.3.13 Nuisance materials

Sheet plastic, carpeting, drywall each require specific handling procedures to promote efficient handling of the rest of the waste stream. When commingled with other construction and demolition waste, these materials are generally picked with hydraulic excavating equipment or grapples—a costly and time-consuming process - before the bulk of waste is loaded onto a chainbelt and passed across a manual sort line.

4.3.14 Material or energy recovery

Backfilling is one way to re-use non-hazardous CDW, specifically in public and earthmoving works. It can help raise awareness to collect, transport and process waste. It can be useful in particular situations, when re-use or recycling into higher quality application is not possible, and can be applied in the context of the waste hierarchy.

However, use backfilling as a last resort option as it has drawbacks: it can undermine the incentives to re-use and recycle in higher value applications. C&D waste should be treated before being backfilled, in order to avoid unwanted environmental effects, such as substances leaching into the groundwater.

Consider all possibilities for recovery as substitute fuel - so-called Refuse Derived Fuels (RDF). The following C&D waste streams are of interest to be used as RDF if the logistics for collection and distribution of it exist:

- contaminated wood and wood-based products that are not suitable for re-use or recycling;
- plastics;
- organic insulation (thermal insulation, sound insulation) materials;
- bitumen based waterproofing membranes.

Make use of the available technologies. Several technologies have been developed for the processing (shredding) of C&D waste for RDF sorting and production. In some countries (for ex., Austria, Pakistan) there are guidelines for processing and using refuse derived fuel (RDF) in the cement industry. In the framework of the Cement Sustainability Initiative (CSI), many other guidelines for RDF-use in the cement industry have been published.

5 Application of end of life strategy to prefabricated multifunctional façade (PMF)

The Multi-functional façade system developed by G&M during the project, is a timber based element aimed at reducing costs, building time and disturbance for occupants during the renovation. In the same time, it enhances construction quality, durability and performances.

The new prefabricated multifunctional façade developed during 4RinEU project do not replace the existing façade, but they are added externally to the existing façade to improve the performances and expand the number of functions of the existing envelope. This innovative technology consists in a prefabricated timber façade module in which some components, such as new windows, decentralized ventilation machine or solar thermal panel are integrated. The off-site prefabrication is useful to reduce the duration of the construction site, and hence to minimize the impact on the building's occupants. The use of timber makes the component potentially environmental friendly as this enables the recycling at the end of life. Moreover, the integration of components gives the advantages of installing, directly in the envelope renovation process, devices (and therefore functions) that increase the energy performances of the building and the comfort of the users.

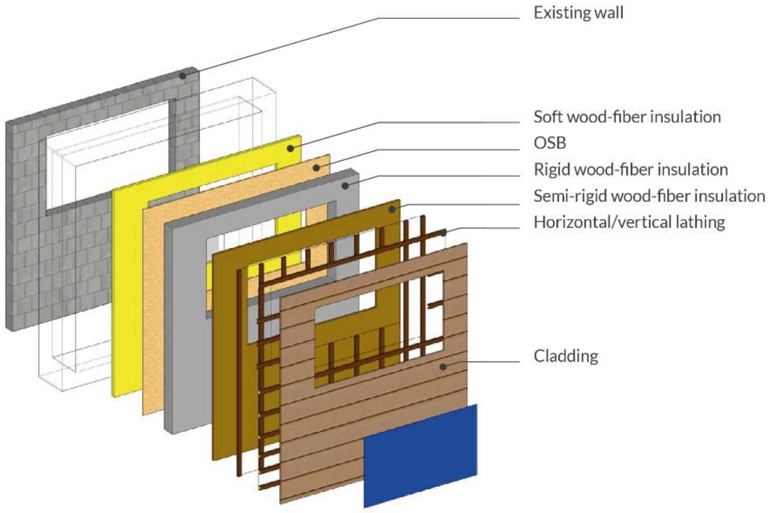

Figure 27: Different components of the Prefabricated Multifunctional Façade

In the modular façade, the different components are integrated within the industrial process. It allows to reach high-insulation level or high thermal capacity depending on the context, with average thermal transmittance after renovation up to 0.25-0.29 W/(m^2K), ensuring high indoor environmental quality conditions, by coupling high thermal comfort, acoustic insulation and healthy.

The system is made of sustainable and recyclable materials, ensuring low costs for disposal.

The choice of an appropriate end-of-life (EOL) destination for discarded products is becoming an important issue for most manufactured products, given the current problems of environmental waste impact and landfill saturation. To address these issues, the design of a product must be optimised with a view to incorporate in that product an environmentally sustainable EOL scenario that respects economic and legislative constraints. The new EOL scenario evaluation method (ELSEM) takes these fundamental aspects into account, and provides a method for evaluating the various options for the EOL scenario of a product during early design phase. The ELSEM provides a simple and intuitive tool for designers to help them constructing arguments for the EOL decision-making process. It is built using the fuzzy technique for order preference by similarity to ideal solution method, a multi-criteria decision process that is highly appropriate in the uncertain and subjective environment in which the designer works during the early stages of product development.

DfEOL is part of a new design approach called ‘design for environment’ (DfE). It endeavours to improve a company’s global environmental performance by reducing the impact generated by each stage of the product life cycle, without compromising other important aspects, such as quality, functionality, and cost[47].

Life Cycle Management in building sector means to put the service life scenarios in the project phase: to choose materials and technical solutions is necessary to know life time expected (temporary building or permanent building), to know the kind of use (optimisation of the use of the spaces by creating multifunctional spaces), to know durability of space and its building components (flexibility and adaptability) and to optimize the service life of the building (by maintenance and components substitution).

Applying Life Cycle Thinking to design, makes it possible to define some Life Cycle Design strategies. All the strategies are based, in a life cycle perspective, on reducing flows of resources (materials and energy): design for reducing means to optimize the quantity of materials and energy used to guarantee building performances. From this fundamental point derive some design strategies:

- Design for reducing (design for lightness)

- Reduce energy and raw materials necessary for producing components
- Reduce energy consumption during transport (using lightweight materials)
- Optimize and intensify the use of spaces with multifunctional spaces

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[47] Pigosso, D.C.A., E.T. Zanette, A.G. Filho, et al. 2010. Ecodesign methods focused on remanufacturing. Journal of Cleaner Production 18: 21–31.

Design to extend useful life of buildings

- Guarantee the possibility, during use phase, of adaptation and flexible use of spaces
- Use materials with the same durability
- Encourage the upgrading and reuse of existing components

Design for maintenance (design to durability of building products)

- Use materials with the long life expected and low maintenance
- Guarantee the possibility, during use phase, of maintenance and cleaning

Design for disassembling (Design for reuse or recycling building components)

- Minimise the number of materials
- Avoid composite materials
- Use finishing that does not contaminate materials
- Reduce the number of components or products
- Use mechanical rather than chemical connections
- Use modular design

Generally light buildings (design for lightness and temporariness) have problems like less durability of components and less comfort (heat retention), but great advantages in flexibility, adaptability and reuse or recycling of building components. Generally heavy buildings (design for durability) are difficult to change and with components that cannot be separated (for recycling and reuse), but their long life "dilute" environmental impacts.

The role of lightness and the role of heaviness is a big question for environment and it is not easy to solve. Only technical solutions chosen during project decision can support the different scenarios of use-maintenance-reuse at building level.

Life Cycle Assessment is an important instrument for evaluating environmental impacts of alternative materials and technical solutions to support design choice. In the building sector it is important to apply Life Cycle Assessment not only at material level, but also at building level, to evaluate alternative strategic design choices.

In the building sector environmental quality of the product does not necessarily mean eco-efficiency of the product "in the building". For this reason, designers need to know the environmental profile of the product, together with other performances: thermal performance, acoustic performance, material resistance, so it is necessary to also have the environmental profile of a product, as an indicator at the moment of the design choice.

EPD can give information on material and product level, but environmental data on the products can be compared only related to the service life of the product in the building use.

For example, in temporary building, where the life time expected is exactly known, comparison of ecological information at production phase has to be integrated with comparison of performance information at use phase according with the specific needs of service life in the building. If the objective of the service life of the building changes, probably the best available technologies or the design strategies for eco-efficiency will also change.

If a designer have to choose the materials to build a wall, probably he will look at thermal performance and he will compare two insulating materials with the same functional unit based on thermal transmission. However, a wall has other performances: for example heat retention. If a designer chose EPS for thermal transmission probably he would need to put it together with a heavy material (like brick) to build a wall with enough thermal mass. But if a designer chooses wood fibre, probably he will build a wall with thermal resistance and heat retention with one material instead of two materials.

If the comparison between two materials is done without a correct functional unit, based on the synergy of all performances required by building, probably the results of the comparison will be incorrect.

EPD data of building's products cannot be compared without knowing the rule of the product in the building.

Comparison of EPD data of alternative building products can be done only if we know the specific building in which products will be assembled. Every building is different and requires different performance by products.

5.1 Components of PMF. Material specification.

With the aim to analyze the sustainability and the possible end of life (EoL) of this façade system, the different materials, specifications and weight are detailed:

Figure 28: Components of the PMF system 1

1. Mineral wool usually 60-80mm (λ=0,035 W/mK ρ= 20kg/m³)

2. Oriented Standard Board (OSB) / OSB/3 usually 15mm (λ=0,13 W/mK ρ≥ 600kg/m³)
3. Timber frame 120 – 300mm; e=83,5cm (λ=0,13 W/mK ρ=450kg/m³) with blow-in cellulose fibre (ISOCELL: λ=0,039 W/mK ρ=60kg/m³)
4. Gypsum fibre board usually 15mm (λ=0,23 W/mK ρ=800kg/m³)
5. Vertical lathing usually 30/50mm (λ=0,13 W/mK ρ=450kg/m³)
6. Horizontal lathing usually 30/50mm (λ=0,13 W/mK ρ=450kg/m³)
7. Timber cladding usually 21mm (λ=0,13 W/mK ρ=450kg/m³)

Figure 29: Components of the PMF system 2

1. Mineral wool usually 60-80mm (λ=0,035 W/mK ρ= 20kg/m³)
2. OSB board / OSB/3 usually 15mm (λ=0,13 W/mK ρ≥ 600kg/m³)
3. Timber frame 120 – 300mm; e=83,5cm (λ=0,13 W/mK ρ=450kg/m³) with blow-in cellulose fibre (ISOCELL: λ=0,039 W/mK ρ=60kg/m³)
4. Wood fibre board 35mm (Steico universal dry: λ=0,047 W/mK ρ=210kg/m³) or wood fibre board 15mm (Egger DHF: λ=0,10 W/mK ρ=600 - 650kg/m³)
5. Vertical lathing usually 30/50mm (λ=0,13 W/mK ρ=450kg/m³)
6. Horizontal lathing usually 30/50mm (λ=0,13 W/mK ρ=450kg/m³)
7. Timber cladding usually 21mm (λ=0,13 W/mK ρ=450kg/m³)

The horizontal lathing / sub-construction depends on the external cladding. If the cladding is vertical the second lathing is needed. If the cladding is horizontal or a facade panel, the second lathing isn´t necessary.

For buildings over 7m high the gypsum fibre board (4) is necessary for the fire safety regulation and for buildings with special use like school or hospital.

For high buildings with over 3 floors a gypsum fibre board (4) is needed for the fire safety regulations. For smaller buildings the wood fibre board is used to optimize the thermal bridges and the U value.

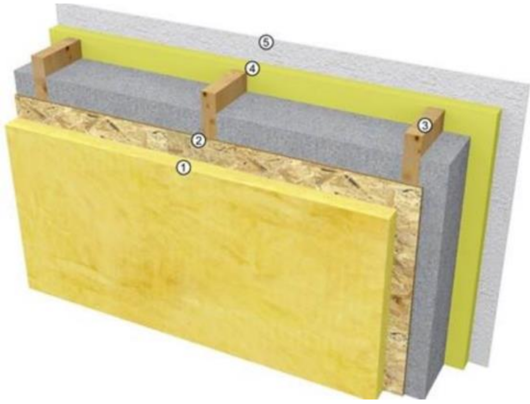

Figure 30: Components of the PMF system 3

1. Mineral wool (usually 60-80mm) (λ=0,035 W/mK ρ= 20kg/m^3)
2. OSB board (OSB/3) (usually 15mm) (λ=0,13 W/mK $\rho \geq$ 600kg/m^3)
3. Timber frame e=83,5cm (λ=0,13 W/mK ρ=450kg/m^3) with blow-in cellulose fibre (ISOCELL: λ=0,039 W/mK ρ=60kg/m^3)
4. Plaster base board; mineral fibre board or wood fibre board (Knauf Tektalan / STO M 046) 60mm
5. Plaster system from Knauf or STO

5.2 Strategies followed by G&M to ensure sustainability at the EoL of their PMF (Current EoL strategies)

Currently, a completely designed strategy for an end of life of the PMF is not being carried out. Until now, G&M do not have any requests from customers nor there are mandatory regulations to be followed. However, G&M consider that looking into the future there might be regulations which require to do end of life management or maybe there might be taxes for difficult to recycle / hazardous waste. In this case, G&M consider that would give them an advantage to be already able to do end of life management, so it makes sense to look at the topic already now although there is no pressure to do so.

G&M use as a marketing argument, that their products have a long life time, low maintenance costs and are environmentally friendly in the disposal.

Here below it is explained why it is environmentally friendly:

- No compound materials which are glued or similar; all mechanical fixations, can be removed relatively easily during the disposal, clean separation of the materials.

- Most materials are based on wood and can be recycled, downcycled or used for energy generation (renewable energy).

- The connection of the different layers of the element is mechanically fastened. Thus, the façade element can be disassembled into the unique components and reused or recycled. In the worst case the timber parts of the façade are burnt and thermally recycled.

5.3 Recommendations for an EOL strategy of the PMF

In order to carry out an End of Life strategy of the PMF the following guidelines and recommendations should be considered:

Intrinsic properties

Materials and products need to fulfill some criteria in order facilitate circularity. We can distinguish intrinsic properties and relational properties. With regard to intrinsic properties, a material or product should be:

1. Of high quality (functional performance),
2. Of sustainable origin, able to ‘reincarnate’ sustainably (after every iteration),
3. Non-toxic (only healthy materials are used),
4. Consistent with biological cycle and cascade, or one or more technical cycles.

Of all the sustainable and non-toxic materials or products applied in a building, the composition and quality performance should thus be defined, as well as the use- and reuse paths. Complex products with multiple short maintenance or redistribution cycles are not necessarily better or worse than homogeneous recyclable products with a high purity and concentration. Furthermore, one should be aware of the fact that the administration required to register all these properties is a learning process rather than a one-off; interventions to the material or product in time will all need to be registered.

Relational properties

Besides their intrinsic qualities, a material or product should relate to the design and use of buildings. These relational properties concern anticipation of unknown future user scenarios. Technically, this can be defined by:

a. Dimensions (taking into account dynamic capacity-demands),
b. Connections (dry and logical),
c. Performance time (defining the lifespan).

Again, similar to the intrinsic properties section, all relevant interventions – e.g. changing partitioning walls – need to be registered.

In separation, neither intrinsic nor relational properties have decisive significance with regard to circularity; it is on the crossing where fulfilment is created. This accentuates the fact that circular construction comprises a dynamic, trans-disciplinary assignment.

Below, seven data categories are listed that can be distinguished with regard to assessing the circularity potential of the PMF:

- Exact composition of the material or product
- Performance quality of the material or product
- Intended (re) use path of the material or product
- Performance time of the material, product, component or service
- Connections applied between materials, products or components
- Dimensioning of materials, products or components
- Quality of the registration system and process

Characteristics and guidelines addressing the process

Guidelines for reuse strategies (process):

- Standardise and use common tools
- Reduce the diversity of components
- Reduce the variation in cores
- Minimise inspection time
- Mark inspection points clearly
- Minimise the number of different materials
- Use standard components
- Avoid components that can be damaged during cleaning process
- Minimise geometric features harming cleaning process
- Identify components requiring similar cleaning processes
- Avoid permanent fasteners that require destructive removal
- Increase corrosion resistance of fasteners
- Reduce the total number of fasteners
- Reduce the number of press-fits
- Standardise and use common fasteners (type and size)

Guidelines for remanufacturing strategy only:

- Minimise disassembly and reassembly time
- Arrange parts and components to facilitate assembly, especially the ones that are easily prone to damage
- Use assembly techniques that allow easy access to inspection points
- Use assembly techniques that allow upgrade
- Use assembly techniques that will withstand overall remanufacturing processes but that will not allow for damage to components that have the potential to be reused/ remanufactured
- Use robust materials to ensure assembly operations

Characteristics and guidelines addressing the product

Guidelines for reuse strategies (product)

- Select reliable materials
- Select reliable components
- Select durable materials
- Select durable and robust components
- Prevent core damage
- Prevent part and surfaces against external environment
- Avoid components that can be damaged during cleaning process
- Standardise and use common materials, components and fasteners
- Standardise and use common interfaces
- Design reusable parts and components
- Facilitate access to components
- Facilitate switch of damaged components
- Provide readable labels, text, and barcodes that do not wear off during the product's service life
- Provide good documentation of specifications, clear installation manuals and testing documentation
- Provide clear information about product, parts, components and materials
- Set up sacrificial parts to give an indication of the components' state of life
- Verify the market acceptance of the offer
- Determine the internal skills needed
- Embed mechanisms into the product to ensure the return of cores
- Facilitate collection of core parts
- Facilitate reverse logistics
- Avoid toxic materials
- Determine the cleaner production and use

Guidelines for remanufacturing strategy only

- Avoid components that can be damaged during inspection process
- Avoid components that can be damaged during disassembly process
- Avoid components that can be damaged during refurbishment process
- Standardise and use common materials, components and fasteners
- Use modular parts and components thus reducing complexity of disassembly because types of assembly techniques are reduced
- Structure the product and parts to facilitate ease of upgrade
- Avoid permanent fasteners that require destructive removal
- Increase corrosion resistance of fasteners
- Standardise and use common fasteners (type and size)
- Reduce the total number of parts, components, fasteners, press-fits and joints

- Specify materials and forms appropriate for repetitive manufacturing

Reused products may not yet be well-accepted on the market[48] nor are design guidelines practical enough for each particular product.

The primary difficulties in implementing the reuse strategies remain. One key parameter concerns the reverse logistic chain, hitherto not well addressed as it mainly depends on company decision-making[49] [50].

Indeed, the crucial step is to retrieve already-used products in pursuit of ensuring direct reuse or remanufacturing. This issue has to be defined from the design stages[50]. That is, the company needs to know where the retired products will be, how to get them back, and how to set up the logistics for bringing them back to the company or to another defined point. These steps may rely on partnerships[51].

The second point is related to the difficulty in putting the strategies in place a posteriori, after the products have been designed and lived[52].

The use of the precedent design guidelines may allow for partial avoidance of such problems, or at minimum, for identification of the weak points ahead.

Guidelines are set up to facilitate the designer's job according to previous studies. Yet, every product is distinct from the others, so that requiring specific parameters may make one guideline irrelevant and may thus not apply.

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6 Conclusions

Deliverable D2.7 provides the 4RinEU guidelines and technology concepts for managing building end of life in order to improve resource efficiency and sustainability management.

An attempt has been made to compile the best recommendations and practices regarding deconstruction approaches to manage the end-of-life of the building components, increasing the recycling rate of the construction materials for the proposed technologies.

The guidelines include recommendations for quick identification of waste material from the existing buildings, technologies for recovery of materials, strategies to optimise the end-of life of 4RinEU renovations and strategies to optimise the end-of-life of components in the building-to-be-renovated – and thus minimise 4RinEU embodied energy.

With the aim to analyze the sustainability and the possible end of life (EoL) management of the Prefab Multifunctional Façade (PMF) manufactured by G&M, the different materials, specifications and weight of the façade were analysed. Recommendations and guidelines were established to follow so that the materials and the assembly techniques used meet some criteria to facilitate the circularity of the PMF at the end of life stage.

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Annex A: European Waste Catalogue

European Waste Catalogue

2014/955/EU: Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council establishes a list of waste defined by six-digit code. The different types of wastes are divided into 20 chapters. The numbers of these chapters are the first two-digit numbers of the waste code.

Chapter 17 groups together “Construction and demolition wastes (including excavated soil from contaminated sites)”, but some waste that can be found on a jobsite can be linked to other chapters. Anyway it is important to state that other sort of waste should be present in the building as furniture, fire safety equipment, etc. that has to be recorded in the waste audit.

The different types of waste that need to be identified, should fit in one of the following groups:

Inert waste - waste that does not undergo any significant physical, chemical or biological transformation. Inert waste will not affect other materials, even if they come into contact in any way likely to produce environmental pollution or harm to human health. Leachability and pollutant content of this waste need to be negligible.

Non-inert non-hazardous waste - This group of wastes can be divided into:

Metals - In general metals are easily recyclable, but if they are polluted or there is a big mixture of metals, they may not be recyclable and could need to be landfilled.

Wood - Wood should be further divided in untreated (clean) wood; wood treated without hazardous substances and wood treated with hazardous substances (which should be treated as hazardous materials)

PVC - PVC can be mechanically recycled easily, but an appropriate sorting is key to optimize PVC recycling rates. Main types of PVC identified are: stiff PVC and soft PVC

Plaster – Mainly represented by gypsum-based construction materials.

Packaging materials - Packaging wastes are subject to specific regulation (Directive 94/62/EC and amendments)

Mixed non-hazardous waste - has the same characteristics as household waste and can be treated by the same processes.

Hazardous waste - Hazardous waste was defined in Directive 2008/98/EC as that showing one or more of the hazardous properties listed in Annex III. Hazardous waste is subjected to specific precautions for their disposal, and is regulated all along Europe.

Considering the different regulations in the different Member States, this section represents only the most common situation in European Countries and should be considered merely as a recommendation.

A non-exhaustive list of materials that can be present in construction and demolition activities is given below.

17 CONSTRUCTION AND DEMOLITION WASTES (INCLUDING EXCAVATED SOIL FROM CONTAMINATED SITES)

17 01 concrete, bricks, tiles and ceramics

17 01 01 concrete

17 01 02 bricks

17 01 03 tiles and ceramics

17 01 06* mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances

17 01 07 mixtures of concrete, bricks, 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* glass, plastic and wood containing or contaminated with dangerous substances

17 03 bituminous mixtures, coal tar and tarred products

17 03 01* bituminous mixtures containing coal tar

17 03 02 bituminous mixtures other than those mentioned in 17 03 01

17 03 03* coal tar and tarred products

17 04 metals (including their alloys)

17 04 01 copper, bronze, 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 09* metal waste contaminated with dangerous substances

17 04 10* 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* soil and stones containing dangerous substances

17 05 04 soil and stones other than those mentioned in 17 05 03

17 05 05* dredging spoil containing dangerous substances

17 05 06 dredging spoil other than those mentioned in 17 05 05

17 05 07* 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* insulation materials containing asbestos

17 06 03* other insulation materials consisting of or containing dangerous substances

17 06 04 insulation materials other than those mentioned in 17 06 01 and 17 06 03

17 06 05* construction materials containing asbestos (7)

17 08 gypsum-based construction material

17 08 01* 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 wastes

17 09 01* construction and demolition wastes containing mercury

17 09 02* construction and demolition wastes containing PCB (for example PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)

17 09 03* other construction and demolition wastes (including mixed wastes) containing dangerous substances

17 09 04 mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

02 WASTES FROM AGRICULTURE, HORTICULTURE, AQUACULTURE, FORESTRY, HUNTING AND FISHING, FOOD PREPARATION AND PROCESSING

02 01 wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing

02 01 08* agrochemical waste containing dangerous substances

03 WASTES FROM WOOD PROCESSING AND THE PRODUCTION OF PANELS AND FURNITURE, PULP, PAPER AND CARDBOARD

03 03 wastes from pulp, paper and cardboard production and processing

03 03 08 wastes from sorting of paper and cardboard destined for recycling

04 WASTES FROM THE LEATHER, FUR AND TEXTILE INDUSTRIES

04 02 wastes from the textile industry

04 02 22 wastes from processed textile fibres

08 WASTES FROM THE MANUFACTURE, FORMULATION, SUPPLY AND USE (MFSU) OF COATINGS (PAINTS, VARNISHES AND VITREOUS ENAMELS), ADHESIVES, SEALANTS AND PRINTING INKS

08 01 wastes from MFSU and removal of paint and varnish

08 01 11* waste paint and varnish containing organic solvents or other dangerous substances

08 01 12 waste paint and varnish other than those mentioned in 08 01 11

08 01 13* sludges from paint or varnish containing organic solvents or other dangerous substances

08 01 19* aqueous suspensions containing paint or varnish containing organic solvents or other dangerous substances

08 02 wastes from MFSU of other coatings (including ceramic materials)

08 02 02 aqueous sludges containing ceramic materials

08 04 wastes from MFSU of adhesives and sealants (including waterproofing products)

08 04 09* waste adhesives and sealants containing organic solvents or other dangerous substances

08 04 10 waste adhesives and sealants other than those mentioned in 08 04 09

12 WASTES FROM SHAPING AND PHYSICAL AND MECHANICAL SURFACE TREATMENT OF METALS AND PLASTICS

12 01 wastes from shaping and

12 01 09* machining emulsions and solutions free of halogens

12 01 14* machining sludges containing dangerous substances

13 OIL WASTES AND WASTES OF LIQUID FUELS (except edible oils, and those in chapters 05, 12 and 19)

13 02 waste engine, gear and lubricating oils

13 02 05* mineral-based non-chlorinated engine, gear and lubricating oils

13 05 oil/water separator contents

13 05 02* sludges from oil/water separators

14 WASTE ORGANIC SOLVENTS, REFRIGERANTS AND PROPELLANTS (except 07 and 08)

14 06 waste organic solvents, refrigerants and foam/aerosol propellants

14 06 02* other halogenated solvents and solvent mixtures

14 06 03* other solvents and solvent mixtures

15 WASTE PACKAGING; ABSORBENTS, WIPING CLOTHS, FILTER MATERIALS AND PROTECTIVE CLOTHING NOT OTHERWISE SPECIFIED

15 01 packaging (including separately collected municipal packaging waste)

15 01 01 paper and cardboard packaging)

15 01 02 plastic packaging

15 01 03 wooden packaging)

15 01 04 metallic packaging

15 01 05 composite packaging

15 01 06 mixed packaging

15 01 10* packaging containing residues of or contaminated by dangerous substances

15 02 absorbents, filter materials, wiping cloths and protective clothing

15 02 02* absorbents, filter materials (including oil filters not otherwise specified), wiping cloths, protective clothing contaminated by dangerous substances

16 WASTES NOT OTHERWISE SPECIFIED IN THE LIST

16 01 end-of-life vehicles from different means of transport (including off-road machinery) and wastes from dismantling of end-of-life vehicles and vehicle maintenance (except 13, 14, 16 06 and 16 08)

16 01 07* oil filters

16 01 13* brake fluids

16 01 14* antifreeze fluids containing dangerous substances

16 02 wastes from electrical and electronic equipment

16 02 09* transformers and capacitors containing PCBs

16 02 11* discarded equipment containing chlorofluorocarbons, HCFC, HFC

16 02 13* discarded equipment containing hazardous components (2) other than those mentioned in 16 02 09 to 16 02 12

16 02 14 discarded equipment other than those mentioned in 16 02 09 to 16 02 13

16 05 gases in pressure containers and discarded chemicals

16 05 06* laboratory chemicals, consisting of or containing dangerous substances, including mixtures of laboratory chemicals

16 06 batteries and accumulators

16 06 01* lead batteries

16 06 02* Ni-Cd batteries

18 WASTES FROM HUMAN OR ANIMAL HEALTH CARE AND/OR RELATED RESEARCH (except kitchen and restaurant wastes not arising from immediate health care)

18 01 wastes from natal care, diagnosis, treatment or prevention of disease in humans

18 01 09* medicines other than those mentioned in 18 01 08

20 MUNICIPAL WASTES (HOUSEHOLD WASTE AND SIMILAR COMM

ERCIAL, INDUSTRIAL AND INSTITUTIONAL WASTES) INCLUDING SEPARATELY COLLECTED FRACTIONS

20 03 other municipal wastes

20 03 01 mixed municipal waste

20 03 07 bulky waste