This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

RE⁴ Project

REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction

D1.3

Overview on the current status of construction of prefabricated elements with recycled materials

Author(s)[1]:	ROS, CETMA, QUB, CBI
Date:	28/02/2017
Work package:	WP1 - Mapping and analysis of CDW reuse and recycling in prefabricated elements
Distribution[2]	PU
Status[3]:	Final
Abstract:	D1.3 summarizes the work performed in Task 1.2 and outlines EU current trends in the reuse/recycling of CDW in prefabricated elements
File Name	RE4_D1.3_Overview on the current status of construction of prefabricated elements with recycled materials_Final_V2.0

Version	Date	Description	Written By	Approved by
0.0	01.12.2016	Draft version	ROS	
1.0	16.02.2017	Revised by CBI	CBI	STRESS
1.1	20.02.2017	Updated version for QC	ROS	ACCIONA, CBI, Creagh
2.0	24.02.2017	Final version	ROS	CETMA

[1] *Just mention the partner(s) responsible for the Deliverable*
[2] *PU: Public, RE: restricted to a group specified by the consortium, CO: Confidential, only for members of the consortium; Commission services always included.*
[3] *Draft, Revised, Final*

TABLE OF CONTENTS

Index of Figures

Index of Tables

ACRONYMS & ABBREVIATIONS

ADR	Advanced Dry Recovery
AAC	Aerated Autoclaved Concrete
BSH	Glue laminated timber
BOF	basic oxygen furnace
CCA	Crushed concrete Aggregate
C&D	Construction and Demolition
CLT	cross laminated timber
CDW	construction and demolition waste
EAF	electric arc furnace
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
glulam	Glue laminated timber
MBT or MRF	mechanical biological treatment plant
MRA	Mixed recycled aggregate
RA	Recycled Aggregate
RMA	Recycled masonry aggregate
RCA	Recycled concrete aggregate
SC	Smart Crusher

1. INTRODUCTION

1.1 Task scope and objectives

The present document is included in the framework of the ongoing RE^4 research project, funded by the European Commission in the context of Horizon 2020 research funding programme, call H2020-EEB-2016. It reports the activities carried out in Task 1.2, led by Roswag Architekten (ROS) with the collaboration of Centro di Ricerca Europeo di Tecnologie, Design e Materiali (CETMA), the Swedish Cement and Concrete Research Institute AB (CBI) and Queen's University of Belfast (QUB).

Task 1.2, Current status of construction of prefabricated elements with reused or recycled material, is included into the context of Work Package WP1 Mapping and analysis of CDW reuse and recycling in prefabricated elements, which was forecasted to begin in Month 1 of the project (September 2016) and to end by Month 9 (May 2017) of the project. In particular, Task 1.2 timing foresaw the activities to be performed from Month 1 to Month 6 (February 2017).
The main goal of the task is to provide an overview about the state of the art in construction with regard to the application of prefabricated elements made from reused or recycled material. The research will be carried out for both concrete and timber construction and will cover aspects such as statistics on use rates of recycled materials for prefabricated elements, requirement definition including any characterisation test for recycled/reused materials/structures from construction and demolition waste (CDW) and any quality control test needed as well as physical-mechanical KPI's of the recycled materials in order to ensure the quality, safety and durability of the resulting prefabricated element. In addition, the LCA and LCC impact of conventional construction versus prefabrication will be elaborated in order to identify the most sustainable way forward. Furthermore, an overview of recycling technologies and plants for different CDW will be provided to identify potential shortcomings for an increased material recovery at an early stage of the project.

Together with the diagnosis of CDW management in the EU (Task 1.1) as well as an overview of the current status on policy measures and regulatory frameworks (Task 1.3) the outcome of this task will form the backbone of the RE^4 project and sets out where construction of buildings with prefabricated elements made from CDW stands to date. In addition, the work will identify but potential knowledge gaps and provide guidance for areas where additional research is required.

1.2 Relevant work package input and output

The activities of Task 1.2 reported in the present document are related to both other tasks of WP1, since they provide an overview about the current status of construction of prefabricated element with reused or recycled materials.

The outcome of this task will form the basis for the design development of the project carried out in WP3, but also inform the physical development of materials, components and elements in WP5. Results will also inform the development strategies for innovative sorting of CDW as well as the development of a BIM-compatible DSS and tool platform for CDW estimation and management (Task 2.5).

1.3 Limitations

For the desk studies carried out for statistical rates of CDW used in prefabricated elements as well as prefabricated construction from concrete and timber CDW no or only limited information was available. This has mainly to do with the fact that recycled concrete or timber is not used yet in prefabricated construction. In the absence of any suitable information with regards to prefabricated construction from CDW, emphasis was put on innovative prefabrication of concrete and timber elements and the reuse of timber elements in order to provide useful information for the design development (WP3) and the physical development of components and elements (WP5).

2. DESCRIPTION OF THE RESULTS

2.1 Statistics on rate of use of recycled materials for prefabricated elements

While at European and national level statistical surveys are available on the volume of CDW and recycled content, there is no data from which the proportion of recycled materials can be directly derived for the production of prefabricated elements. A differentiation according to prefabricated elements for different application purposes such as foundations, ceiling slabs, support structures etc. is not possible according to the available statistical data.

In terms of mineral construction waste, recycled aggregates from CDW account for 8 % of the total aggregate demand required in Europe, according to the "Annual Review-2015-2016" of the European Aggregates Association, with large differences between countries in Europe as shown in Figure 1 for the period of 2005-2006. In the United Kingdom as well as in the Netherlands one fifth of the total aggregate used is covered by recycled aggregates. Newer data tend to show the same distributions.

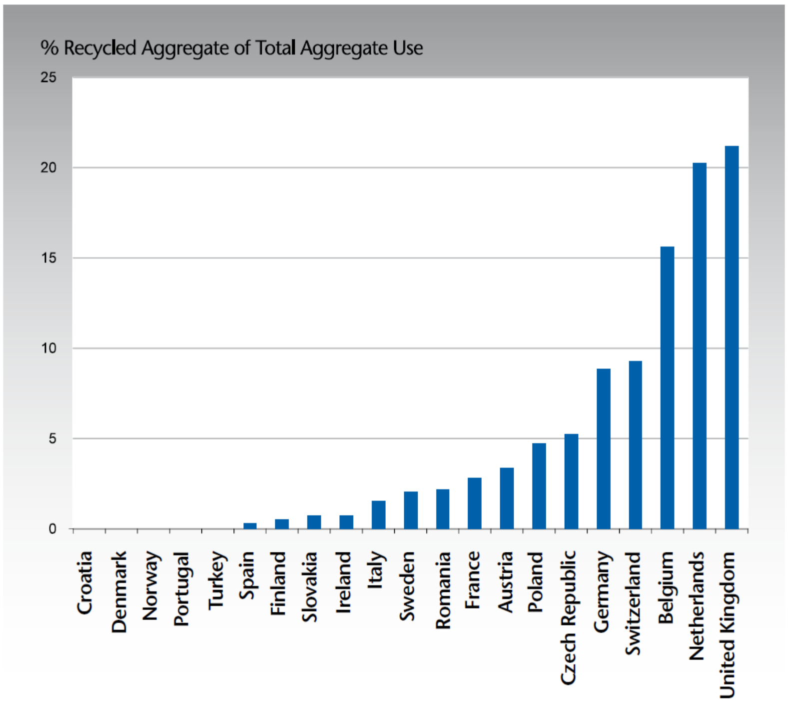


Figure 1: Data from UEPG 2005 and 2006 statistics.

Source: "The Cement Sustainability Initiative- Recycling Concrete, Executive summary" from World Business Council for Sustainable Development – WBCSD, Switzerland

Of the total aggregate demand in Europe, 15 % are used in the precast concrete industry (Figure 2). The extent of the share of recycled aggregates in the precast concrete industry is not yet statistically recorded at European or national level. Information on the application of mineral construction waste for other prefabricated elements like e.g. masonry elements is not available. [1]

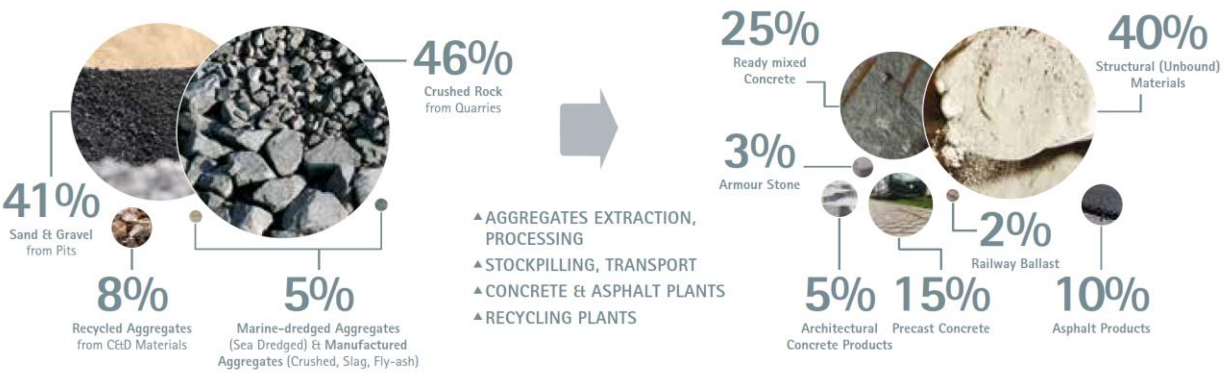


Figure 2: Sources and intermediate uses of aggregates.

Source: UEPG Annual Review 2015-2016 EUROPEAN AGGREGATES, ASSOCIATION - A Sustainable Industry for a Sustainable Europe, UEPG aisbl, Rue d'Arlon 21, 1050 Brussels, Belgium

As an example of national surveys of the recycling of mineral construction waste, the German workgroup "*Kreislaufwirtschaft Bau*" (circular economy construction) is mentioned here, which produces every two years a monitoring report on the emergence and retention of mineral building waste. The latest report is from 2015 (data base 2012). In addition to the recycling rate, data are also provided on the use of recycled building materials. According to this report, 19 % of recycled building materials are used in asphalt and concrete production in Germany. However, more detailed information on the use of recycled building materials in the prefabricated component industry is not given here either. [1]

The statistical surveys on the exploitation of wood from CDW at European level also do not allow any conclusion to be drawn about their use in prefabricated elements. This is also due to the fact that CDW wood is usually not recorded individually as a separate category.

For example, the "Annual Review-2015-2016" of the European Aggregates Association [1] contains information on the recycling rate of different types of material from CDW, but wood is grouped with glass, metal, plastic and gypsum.

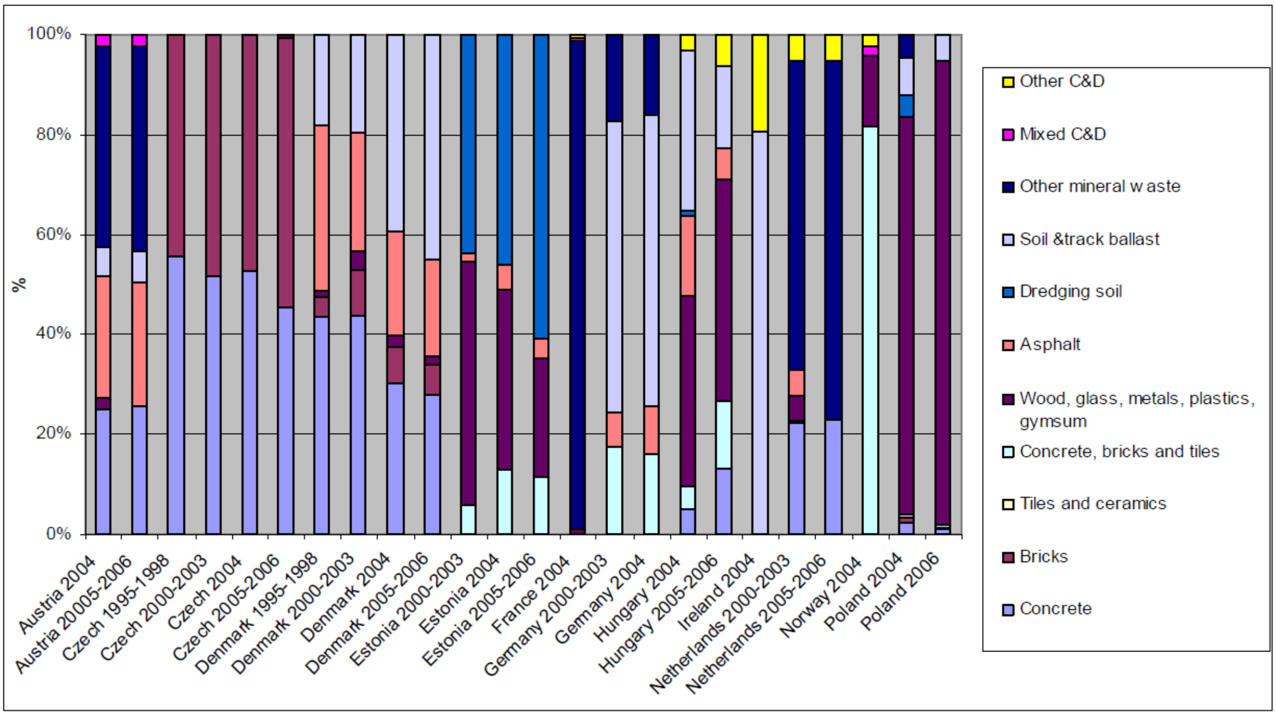


Figure 3: Percentage composition and development of recycled construction and demolition waste in the EU and Norway, Source: ETC/RWM, 2008 based on national reports and statistics

In this report, no details are given on the type of recovery or the application of the recycled wood from CDW.

Mantau, U. et al. [4] contains information on the utilization of so-called post-consumer wood, which "comprises packaging materials, demolition wood, timber from building sites, and fractions of used wood from residential (municipal waste), industrial and commercial activities". Wood from CDW is not listed individually.

Accordingly, in 2007, 18.1 Mm³ clean post-consumer wood was used for chipboard production. The rate of re-use of post-consumer wood is higher in the Northern and Western European countries, because it is used as a resource for the panel industry or other material uses. However, no values are given for prefabricated wooden elements. Data on the nature and size of the post-consumer woods are not made available, which would be essential in order to assess their suitability for use in prefabricated elements.

According to Meinlschmidt P. et al. [5], the material use of waste wood takes place mainly in the wood-based material industry in Germany for the production of chipboards. The proportions of roundwood, industrial waste and recycled wood in the production of chipboard differ strongly between the European countries, as the Table 1 illustrates.

	Share of roundwood in %	Share of industrial waste wood in %	Share of recycled wood in %
Germany	20	46	34
France	41	37	22
Italy	0	5	95
Poland	38	47	15
Spain	31	41	28
Austria	20	45	35
UK	16	31	53

Table 1: Wood used in the production of chipboards [5]

Although extensive data for mineral construction waste and wood waste are collected at European level and published in a variety of ways, they do not permit conclusions as to whether and to what extent recycled materials are used for prefabricated elements. With mineral construction waste, it is only possible to estimate the potential as a "raw material" for prefabricates element industry.

2.2 Requirement definition including any characterisation test for recycled/reused materials/structures from CDW and any needed quality control test, physical-mechanical KPI

2.2.1 Concrete Construction

In many European countries the main CDW product is recycled aggregate which is either used as a recovery material on landfills (i.e. temporary haul roads or daily cover) or as unbound material for pipe bedding, sub-base and base courses in highway pavement construction. However, a number of standards, specifications, recommendations and guidelines exists in various European countries for the use of recycled aggregate in non-structural concrete (such as non-load bearing façade panels or non-load bearing partition walls), structural concrete (such as foundations, support structure or load bearing partition walls) or both non-structural and structural concrete. A detailed review of these standards is given by Concalves and de Brito [6] and Dhir et al. [7]. More specifically:

In Germany, DIN 4226-100:2002-02 [8] sets the requirements for the use of recycled aggregates in the production of mortar and concrete. Recycled aggregates are classified into four types: concrete rubble (Type 1), demolition debris (Type 2), masonry rubble (Type 3) and mixed rubble (Type 4). In addition, the Guideline: Concrete with recycled aggregate derived from concrete rubble published by the German Committee of Reinforced Concrete (DAfStb) [9] sets the requirements for the use of recycled coarse aggregates in concrete. More specifically: concrete rubble or demolition debris can be used in the production of structural concrete (Exposure classes X0, XC1-XC4, XF1-XF3 and XA1 in accordance with EN 206:2013+A1:2016 [10]), whereas masonry rubble or mixed rubble can only be used in non-structural concrete. The maximum replacement levels of virgin aggregate by concrete rubble (Type 1) or demolition debris (Type 2) are set at 35% and 25 % for manufacturing C25/30 and C30/37 concrete, respectively. Allowable limits of contaminants and aggregate property requirements are shown in Table 2 below.

Type	Concrete content (%)	Masonry content (%)	Max. contaminants content(1) (%)	Max. chloride content (%)	Max. sulfate content (%)	Min. density (kg/m^3)	Max. water absorption (%)
1	> 90	< 10	1	0.04	0.8	2000	10
2	> 70	< 30	1	0.04	0.8	2000	15
3	< 20	> 80	1	0.04	0.8	1800	20
4	Concrete + Masonry content > 80		n/a	0.15	n/a	1500	n/a

1-Bituminous materials are not included.

Table 2: Recycled aggregate composition and property requirements for use in the production of concrete [8]

In Portugal, specification E471 published by the Portuguese National Laboratory of Civil Engineering [11] sets the requirements for the use of recycled coarse aggregates in the production of concrete. Recycled aggregates are classified into three types: ARB1 (Recycled concrete aggregates), ARB2 (Recycled concrete aggregates) and ARC (Mixed recycled concrete and masonry aggregates). ARB1 and ARB2 can be used in the production of structural concrete (Exposure classes X0, XC1-XC4, XS1 and XA1 in accordance with EN 206:2013+A1:2016 [10]), whereas ARC can only be used in non-structural concrete. The maximum replacement levels of virgin aggregate by ARB1 or ARB2 are set at 25% and 20% for manufacturing C35/45 and C40/50 concrete, respectively. Allowable limits of contaminants and important aggregate property requirements are shown in Table 3 below.

Type	Concrete content (%)	Masonry content (%)	Max conta-minants content(1) (%)	Light-weight material content (%)	Max. chloride content (%)	Max. sulfate content (%)	Min. density (kg/m^3)	Max. water absorp-tion (%)
ARB1	> 90	< 10	0.2	1	a.i.	0.8	2200	7
ARB2	> 70	< 30	0.5	1	a.i.	0.8	2200	7
ARC	Concrete + Masonry content > 90		2	1	a.i.	0.8	2000	7

1 - It includes organic material.

a.i. - additional information is provided by the Portuguese National Laboratory of Civil Engineering.

Table 3: Recycled aggregates composition and property requirements for use in the production of concrete [11].

In UK, BS 8500-2:2015+A1:2016 [12] which is the complementary standard to EN 206:2013+A1:2016 [10] sets the requirements for the use of recycled coarse aggregates in the production of concrete. Recycled aggregates are classified into two types: Crushed Concrete Aggregate (CCA) which is produced by crushing hardened concrete of known composition that has not been in use and has not been contaminated during storage or processing and Recycled Aggregate (RA) produced from demolition waste which contains concrete, masonry and asphalt. CCA can be used in the production of structural concrete (Exposure classes X0, XC1-XC4, XF1 and DC-1 in accordance with EN 206:2013+A1:2016 [10]), whereas RA can only be used for non-structural concrete. The maximum replacement level of virgin aggregate by RCA is set at 20% for concrete classes RC20/25 to RC40/50. Allowable limits of contaminants are shown in Table 4 below.

Type of aggregate	Max. clay and masonry content (%)	Max. fines content (%)	Max. floating material by volume cm^3/kg	Max. bituminous material content (%)	Max. other materials(1) (%)	Max. acid soluble sulfate (%)
CCA	10	4	2	5	1	0.8
RA	100	4	2	10	1	*

1-It includes clay, soil, metals, wood, plastic, rubber, gypsum plaster and glass.

*-To be determined on a case by case basis.

Table 4: Recycled aggregates composition requirements for use in the production of concrete [12].

In the Netherlands, recommendations published by the Centre for Civil Engineering Research and Codes (CUR) [13] set the requirements for the use of either recycled concrete aggregate (RCA) or recycled masonry aggregate (RMA) in the production of plain, reinforced and pre-stressed concrete (non-aggressive environments). More specifically, if the replacement level of virgin aggregates (both fine and coarse aggregates) by recycled aggregates is less than 20% then the total (both virgin and recycled) aggregate content is considered to be similar to that of virgin aggregates. However, if the level of replacement is more than 20%, correction factors are used for some materials properties during the design of various concrete structural elements. The maximum concrete strength class that can be produced using recycled aggregate is C40/50.

Allowable limits of contaminants and important aggregate property requirements are shown in Table 5 below.

Type of aggregate	Concrete content (%)	Masonry content (%)	Max. organic material content (%)	Max. contaminants Content (%)	Max. lightweight materials content (%)	Max. chloride content(1) (%)	Max. sulfate content (%)	Min. density (kg/m^3)
RCA	> 95	< 5	0.1	1	0.1	0.05	1	2000
RMA	–	> 65	1	1	n/a	0.05	1	2000

1-Values valid for reinforced concrete. Different values apply for plain or pre-stressed concrete.

Table 5: Recycled aggregates composition and property requirements for use in the production of concrete [8].

In Switzerland, instruction technique (tV) 70085 published by the ARMASUISSE federal agency [14] sets the requirements for the use of recycled coarse and fine aggregates in the production of concrete. Recycled aggregates are classified into two types: recycled concrete aggregates (RCA) and mixed recycled concrete and masonry aggregates (MRA). RCA can be used in the production of reinforced and pre-stressed concrete (for pre-stressed concrete additional tests are required), whereas MRA can only be used in non-structural concrete. For structural concrete, if the replacement level of virgin aggregate is less than 20% then the total (both virgin and recycled) aggregate content is considered to be similar to that of virgin aggregate. However, if the level of replacement is more than 20%, correction factors are used for material properties such as modulus of elasticity, creep and shrinkage during the design of various concrete structural elements. The maximum structural concrete strength class that can be produced using RCA is C30/37. Allowable limits of contaminants and important aggregate property requirements are shown in Table 6 below.

Type of aggregate	Concrete content (%)	Masonry content (%)	Max. contaminants content (%)	Max. chloride content (%)	Max. sulfate content (%)
RCA	< 100	–	1(1)	0.03	1
MRA	< 100	–	1	n/a	1

1-Bitouminous and lightweight materials are not included.

Table 6: Recycled aggregates composition and property requirements for use in the production of concrete [14].

In Belgium, standard PTV 406 [15] published by the Impartial Certification Body in the Construction Sector (COPRO) sets the requirements for the use of recycled coarse aggregates in the production of concrete. Recycled aggregates are classified into three types: recycled concrete aggregates (RCA), recycled masonry aggregates (RMA) and mixed recycled concrete and masonry aggregates (MRA). The allowable limits of contaminants for the above three types of recycled aggregate are shown in Table 7 below.

Type of aggregate	Concrete content (%)	Masonry content (%)	Max. organic material content (%)	Max. contaminants content[(1)] (%)
RCA	> 90	< 10	0.5	0.5
MRA	> 40	> 10	0.5	1
RMA	< 40	> 60	0.5	1

1-Bitouminous materials are not included.

Table 7: Recycled aggregates composition requirements for use in the production of concrete [15].

In Spain, Code on Structural Concrete EHE-08 takes a positive view of the use of recycled aggregates in concrete structures. This Code recommends limiting the content of coarse recycled aggregate up to 20% by weight out of the total weight of coarse aggregate. With this limitation, the final properties of recycled concrete are hardly affected compared to results obtained for conventional concrete. For higher percentages, special studies and complementary experiments are required for each application. Recycled aggregate may be used for mass concrete and reinforced concrete with characteristic strength no greater than 40 N/mm2 while its use in prestressed concrete is excluded. In the case of the manufacture of non-structural cement, up to 100% of recycled coarse aggregate may be used.

Finally, RILEM TC 121-DRG recommendation [16] sets the requirements for the use of recycled coarse aggregates in the production of concrete. Recycled aggregates are classified into three types: aggregates which mainly come from masonry rubble (Type 1), aggregates which mainly come from concrete rubble (Type 2) and aggregates which are a mix of recycled and natural aggregates (with at least 80% natural aggregates and up to 10% Type 2 aggregates) (Type 3). Type 2 and 3 aggregates can be used for structural concrete, whereas Type 1 can only be used for non-structural concrete. The replacement level of coarse virgin aggregates can be up to 100% by Type 3 aggregates (Exposure conditions: dry or wet environment, non-aggressive soils and/or water not exposed to frost) with no limit set regarding strength class. The maximum structural concrete strength class that can be produced using Type 2 aggregate is C50/60. Finally, the maximum non-structural concrete strength class that can be produced using Type 1 aggregate is C16/20. Allowable limits of contaminants and important aggregate property requirements for Type 1, 2 and 3 aggregates are shown in Table 8 below.

Type of aggregate	Concrete content (%)	Masonry content (%)	Max. organic material content (%)	Max. contaminants content (%)	Max. lightweight material content (%)	Max. filler content (%)	Max. water soluble chloride content (%)	Max. sulfate content (%)	Min. density (kg/m^3)	Max. absorption (%)
1	–	< 100	1	5	1	3	1	a.i.	1500	20
2	< 100	–	0.5	1	0.5	2	1	a.i.	2000	10
3	< 20	< 10	0.5	1	0.5	2	1	a.i.	2400	3

a.i.- additional information is provided by RILEM.

Table 8: Recycled aggregates composition and property requirements for use in the production of concrete [11].

2.2.2 Timber Construction

In Scandinavian countries such as Sweden and Finland a large percentage of CDW is wood due to its extensive use in the construction of residential buildings [17] [18]. Wood also forms a significant percentage of the overall CDW created in Germany and Austria [19] [20] [21]. Wood waste can be efficiently recycled or re-used if the required recycling or re-manufacturing infrastructure exists. However, during its service life, structural timber quality may deteriorate due to moisture, contamination or excessive loading. Consequently, wood waste is not always suitable for recycling or re-use. In addition, pre-treatment of wood waste containing foreign objects (i.e. iron/steel nails), paint or veneer may be labour intensive and expensive. A limited re-use of timber structural elements (such as beams) as well as doors and windows is taking place in Sweden and Finland (however, no specific national standards dealing with the re-use of structural timber were identified). In addition, research is currently taking place to develop new products such as panels and wood-plastic composites by using fibres from wood waste (however, proper evaluation of such products should be performed, especially when wood fibres are mixed with other materials) [17] [18]. In Germany and Austria wood recovered from CDW is mainly used for fuel either in chipped or pelletized form. Wood waste is also extensively used in the production of engineered wood (fibreboard, particleboard and oriented strand board), mulch (in horticultural and agricultural applications) and animal bedding [20].

2.3 Overview of prefabricated concrete construction with CDW

2.3.1 Limitations

The main limitation of prefabricating whole elements using RC-concrete lies within their production. RC aggregates are known to have significantly increased water absorption rates when compared to natural aggregates [22]. Precast concrete elements are cast using a low water/cement ratio to ensure a quick (within hours) hardening process. If the absorption rate of the aggregate cannot be predicted reliably, production might be crippled. Increased water absorption also leads to increased drying shrinkage, which has to be taken into account when building moulds.

Apart from that, batch qualities of RC-aggregates might differ from each other depending on where they were acquired.

Regulations on prefabricated concrete parts in Germany can be found in DIN 1045-4: 2012-02 "Concrete, reinforced concrete and pre-stressed concrete structures - Part 4: Complementary rules for the production and conformity of finished products", which refer to EN 12620: 2008-07 "Concrete reinforcement for concrete" and DIN EN 206: 2017-01 "Concrete - Definition, properties, manufacture and conformity" with regard to the grain. In DIN EN 13369: 2013-08 "General rules for precast concrete parts" the RC aggregates would be mentioned in Annex Q.

On the occasion of the meeting „Neues Bauen – eine Chance zur Abfallvermeidung im Bausektor "(engl.: "New Building - an Opportunity to Avoid Waste in the Construction Industry"), which took place in Stuttgart in early February 2017, Prof. Sylvia Stürmer from the University of Applied

Sciences of Konstanz, Faculty of Civil Engineering expressed her opinion on the use of RC grit in precast concrete as follows:
“In the production of "normal" precast concrete elements, fast setting Portland cements (CEM I) and low w/c values are generally used. The hydration is accelerated considerably by high temperatures in the precast factory so that the transport strength is achieved within hours and the standard strength within days. However, the use of RC-aggregates can significantly influence the hydration process in the concrete, since post-hydration of previously unset cement particles can occur. Due to the short time window in precast concrete element production and the fluctuations in RC-aggregates batches, this can make it difficult to achieve a high quality product.
For visual reasons, prefabricated concrete with a higher proportion of cement is used in the edge layers in order to achieve a smooth surface finish. This technique could help make precast elements containing RC-aggregates visually indistinguishable from conventional elements.”
In principle, no reasons against the use of RC grains in prefabricated concrete were found in Prof. Stürmers research, but it was postulated that pre-stressed precast concrete parts and water-resistant concrete components could be produced.
More detailed results were requested from the project manager, but are not yet available for more detailed explanations. The study in which Prof. Stürmer was involved was funded by the BWPLUS-programme and led by Karlsruhe Institute of Technology (KIT).

In spite of this, there are great chances of the application of RC grain, especially in the production of concrete products such as paving stones. The company Feess GmbH claimed to have exceeded the strength class C30/37 by 60% in the case of its concrete goods with type 2 grain, that is, with up to 30 % ceramic material ("red grain") in RC grains.
There are a few product examples of precast RC-concrete products, e.g. Feess GmbH's “Ökostone” [23] (Figure 4) or a similar stone by Hans Wolf GmbH (Figure 5).

Figure 4: Concrete mix with mineral CDW aggregates for precast stone production

Source: Hans Wolf GmbH & Co. KG

Figure 5: Precast concrete stones made from mineral CDW aggregates

Source: Hans Wolf GmbH & Co. KG

These stones, however, are not used for building construction purposes. The above-mentioned companies use them without mortar for partition walls of their mineral aggregate heaps.

2.3.2 RC-stone and RC-mortars from aerated concrete recycled

Within the scope of a research project conducted by the "Amtliche Materialprüfungsanstalt" of the Free Hanseatic City of Bremen (MPA Bremen) in co - operation with the Research Association for Recycling and Recovery of Reusable Materials in Construction (RWB Bremen) and the University of Applied Sciences in Bremen, Germany, building stones and mortars were produced from aerated concrete recycled for non-bearing interior walls and used in a demonstration project. The recycled used was deliberately derived from demolition waste and not from production-grade of aerated concrete production, in order to be able to test the possibilities of using the aerated concrete recycled from demolition waste. The developed cement-containing mortars made with aerated concrete recycled were optimized by the addition of fibres and additives and were demonstrably suitable as lightweight mortars and basic plaster for renovation plaster systems. The developed light building stones had properties that are more than adequate for application as non-load-bearing masonry.
Both for the mortar and for the light stones, the formulas developed under laboratory conditions were successfully transferred to industrial production. [24]

2.3.3 Autoclaved masonry stones with mineral CDW aggregates

The development of a recycling masonry stone using mineral demolition material and the application of lime sand brick technology (autoclave hardening) was promoted by the research initiative "ZukunftBau" of the Federal Office for Building and Regional Planning, Bonn, Germany. Investigated were formulations with the addition of sorted and contaminated lime-sand recycled material, brick recycling material, aerated concrete recycling material and concrete recycling material, each of which was replaced by up to 75 % of the natural sand used. The suitability for the erection of buildings with comparatively lower demands on the masonry compressive strength (e.g. one- and two-storey housing construction) could be substantiated. In order to counteract the quality characteristics by the addition of recycled material, the proportion should be limited to a meaningful measure. It was also found that finer fractions of up to 2 mm were less disadvantageous than coarser RC grains. Adhesive remnants of other building materials and inorganic as well as organic foreign substances also led to a reduction in the strength and to other losses in the quality characteristics of the developed masonry stones, which is why they should be sorted out or removed prior the use. It was tested by means of the production technology measures that can be counteracted by the addition of the RC materials. However, these were partly associated with higher costs and primary energy consumptions and their suitability has to be evaluated in individual cases. The results of the research project were made available to manufacturers of lime sand bricks in Germany to enable rapid implementation in practice. There are no figures available for the actual disposal of such recycled masonry stones. [25]

2.4 Overview of prefabricated concrete construction without CDW

Precast concrete elements have been widely used for decades. Their material efficiency and guaranteed quality through a controlled fabrication process make them an ideal substitute for in-situ concrete.

2.4.1 Basic principles

There are several basic principles which make building with precast concrete elements efficient and productive [26]:

– even construction grid of load-bearing structure
– bracing cores adjusted to grid spacing
– if possible, no variation in ceiling height
– standardised ceiling openings for utilities according to grid spacing
– a great number of identical elements (series)
– limited transport dimensions and assembly loads
– standardized profiles and nodes
– the larger the series, the better the degree of formwork capacity utilisation.

Although element size is limited, a large element like a multi-span girder or a multi-storey column minimizes alignment effort and number of connections, which greatly enhances efficiency.

2.4.2 Transport

Although transport distance of prefab concrete elements should be kept to a minimum in order to reduce CO_2 emissions, road transport still defines limiting size and weight values of the elements.

2.4.3 Dimensional limitations

For the European Union, maximum dimensions and weight for road transport are regulated in Council Directive 96/53/EC annex 1.

Maximum weights and dimensions of vehicles	
Length [m] of articulated vehicle	16.5
Distance [m] between king pin and rear of a semi-trailer	12
Length [m] of a trailer	12
Width [m] of any vehicle, except conditioned vehicles	2.55
Height [m] of any vehicle	4
Gross weight [t] of vehicles with five or six axles	40

Table 9: Maximum transport weight and dimensions according to EU Council directive 96/53/EC annex 1 **Errore. L'origine riferimento non è stata trovata.**

These values can be exceeded with special permits. However, the issue of these permits depends on numerous factors such as transport routes and bridge load-bearing capacities, which is likely to prolong shipment time and increase financial strain for all involved parties.

2.4.4 Transport anchors

Special attention must be paid to the nature and number of transport anchors. Thin parts like non-load-bearing facade panels receive high loads when being lifted and are especially susceptible to damage. In many cases, this load case defines structural design of the element.
Visible corners and edges must be treated carefully to prevent chipping.

2.4.5 Assembly

Depending on their size, between 10 and 30 parts can be put in place daily [26] in residential construction. Some factors might reduce this performance, such as:

– extreme weather conditions
– difficult logistic situation on construction site
– custom instead of serial elements
– complicated connection of precast elements

An instruction manual which specifies the correct order of assembly and guarantees structural integrity throughout this process must be provided [26].

2.4.6 Precast elements

Although it is common to use semi-precast elements that are cast together on-site, they are omitted in this report because being unsuitable for disassembly.
Span lengths depend on self-weight and imposed load and usually vary between 5 m and 10 m for residential and office applications.

Foundations
In most cases, foundations of precast concrete structures are cast in place, but there are also several precast foundation elements available on the market.
Foundations are especially exposed to moisture and freeze/thaw attacks. Therefore, the concrete mixes have to be sufficiently resistant to these effects.

Individual foundations
Precast individual foundations can be equipped with cast-in bolts to screw on the columns (Figure 6). Alternatively, they can be directly cast on the columns (Figure 7). This however is limited to a foundation edge length of 3 m x 3.5 m [26]. The cast-on foundation is most economic due to its smaller foundation depth and short construction time.
Pocket foundations are also used regularly but require casting the column in which is not reversible.

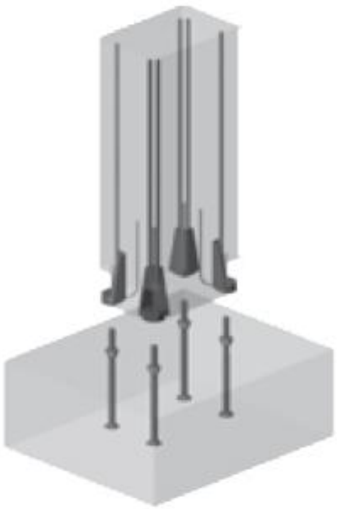


Figure 6: Block foundation with cast in bolts
Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Figure 7: Column with cast-on foundation
Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Strip foundations
A few manufacturers offer precast strip foundation beams, which can be placed on pile foundations or precast blocks. These beams can have up to 1 m edge length [28] and are made

from high strength highly resistant concrete mixes. They are joined together using bolts and grout (Figure 8).

Slab foundations

Some manufacturers offer precast foundation slabs. These elements must be connected using tension rods to ensure structural integrity (Figure 9). Their use does not seem to be widespread. Individual slabs, which are not interconnected, are used for shed and garage foundations (e.g. Vroom NL: Prefab shed floor)

Figure 8: Vroom Precast strip foundation

Source: Vroom Foundation Technology, NL

Figure 9: Precast slab foundation

Source: Oldcastle precast, Inc.

Pile foundations

Pile foundations can be driven into the soil to improve its load bearing capacity. Their profile edge length varies between 220 and 500 mm, their length up to 7.5 m [29]. These piles are used to improve soil conditions for heavy loads. If extracted upon dismantling a building, they would probably be destroyed due to high tensile stress.

Columns

A rectangular profile is most efficient, since the elements are generally cast in a horizontal position. Cylindrical columns require being cast vertically, which increases cost and effort [26]. Formwork is most economic if the columns 'shape resembles an extruded 2D profile, e.g. consoles on two opposite sides (Figure 10a).

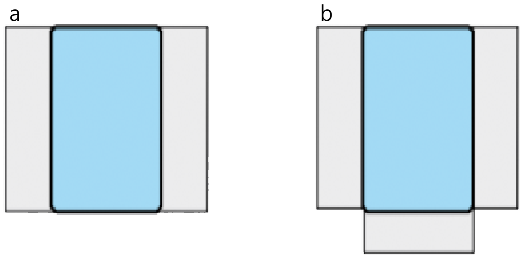


Figure 10: Economic and less economic column profiles, Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

For industrial applications, columns are usually several stories high. This has advantages in efficiency, but column length is limited to approx. 3 stories and sound-proofing might become an issue. Columns longer than 3 stories have to be joined together. These joints should be offset from each other in order to improve stiffening effects. The connection can either be screwed using cast-in steel parts or grouted [26].

When using single-storey columns advantages are a high rate of repetition and low column weight and dimensions [26].
Restrained columns are either screwed on the foundations, cast into sleeve/block foundations or come with their individual foundation attached to them.

Beams
Precast beams feature angular profiles and can be manufactured in different shapes to support different slab types (rectangle, inverse T-shape, inverse U-shape)
They are normally not pre-stressed [26].
When used in combination with multi-storey columns, the beams are commonly notched and act as a single-span girder.
When used in combination with single-storey columns, the beams can be produced in full length and act as multi-span girders.
Edge beams with asymmetrical consoles must be constructed in such a way that they transmit torsion moments caused by the slabs to the adjacent columns [26]. This can be avoided by connecting the slabs centrically on the edge beam.

Roof and ceiling slabs
Roof slabs are generally similar to ceiling slabs, but may be made of aerated concrete to increase insulation and decrease weight, since they normally do not have to be as resistant as ceiling slabs.
There are several methods of constructing fully precast roof and ceiling elements.

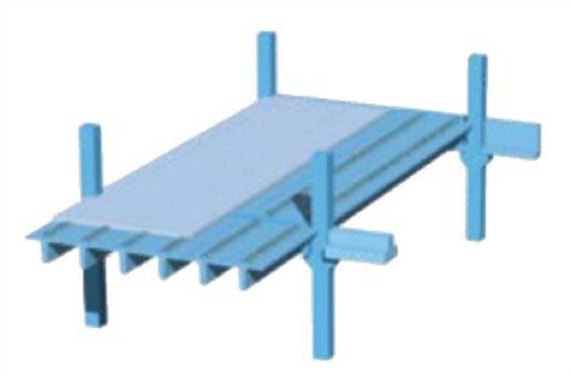


Figure 11: Semi-precast TT-slab elements on inverse T-beams on multi-storey columns

Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Figure 12: Hollow-core slab elements on inverse T-beams on multi-storey columns

Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Solid and hollow core slabs

Solid core slabs (Figure 13a) are less material efficient and heavier than hollow core slabs.

Hollow core slabs (Figure 13b) can be either cast with our without pre-stressing. They have the advantage of a flat finished surface as a ceiling.

They are suitable for full prefabrication and can be cast with a width up to 4.5 m [26].

Pre-stressed hollow core slabs

Pre-stressed ceiling slabs (Figure 13b) are economic if the span length is high. They can span up to 16 m with a maximum height of 400 mm. Their width is limited to 1.2 m [26]. This technique offers very high floor plan flexibility and can be used without suspended ceiling, but soundproofing might pose an issue.

TT-Slabs

TT-Slabs can be produced with or without pre-stressed properties. They are suitable for industrial applications and can support heavy distributed loads, e.g. car parks. When compared to hollow core slabs, these slabs allow easier installation of utilities due to their shape (Figure 11 and 13c).

Trough slabs

Trough slabs are less material efficient than TT-Slabs but perform better with single point loads [26]. Also the element's edges might allow for easier shear resistant connections between the elements (Figure 13d).

The above-mentioned slab construction methods all act as a single-span girder and have to be connected into a force-locking manner to achieve the horizontally stiff plate effect. This is commonly done by grouting the gaps [26].

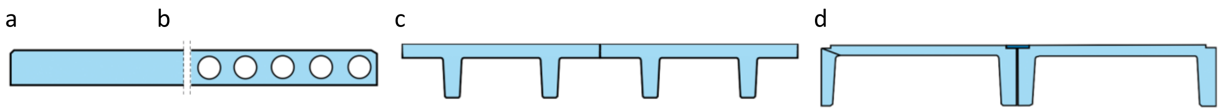


Figure 13: Solid, Hollow Core, TT- and Trough slab profiles (from left to right)
Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Horizontal, vertical and diagonal bracing
Vertical bracing can be achieved through cores, walls, frames, clamped columns and diagonal bracing.

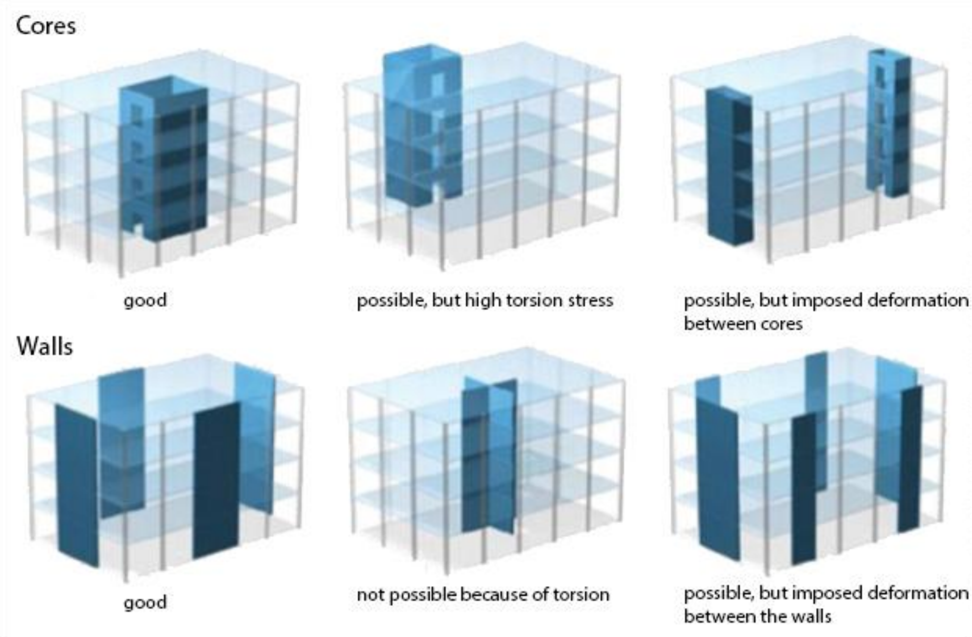


Figure 14: Possible and impossible types of vertical bracing through cores and walls
Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Bracing through cores and walls is considered standard procedure in current precast construction [26]. This has some disadvantages: Cores are generally cast on-site or come in semi-precast elements, which are not suitable for disassembly. Bracing walls predetermine the building's floor plan and appearance through a strict and visible pattern (Figure 14).
Horizontal bracing with stiff frames or clamped columns lead to great bending stress and should be limited to structures with no more than two storeys [26].
Diagonal bracing (Figure 15) acts similar to wall bracing, but leaves more flexibility for openings in the façade.

Figure 15: Bracing truss with precast concrete elements

Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Outer Walls

Precast facade sandwich elements with an integrated insulation layer are economic and widely used. Their typical layer thickness is 100 - 200 mm for the load-bearing layer, 60 - 120 mm for insulation and 70 - 100 mm for the outer layer (Figure 16).
According to DIN 1045-1 minimum thickness of the outer reinforced concrete layer must be 70 mm, concrete cover to reinforcement must be 25 mm.

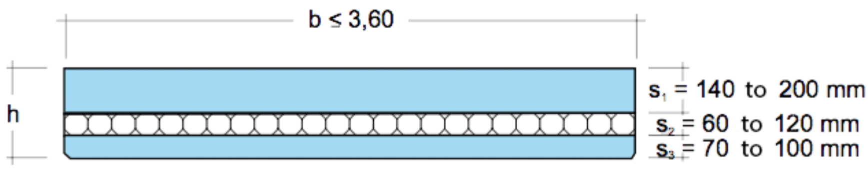


Figure 16: Precast sandwich façade panel with load-bearing, insulation and cladding layer, Source: FDB e.V. / Verlag Bau+Technik GmbH Düsseldorf

Facade panels can also be clad with other materials, such as steel.
Alternatively, solid aerated concrete can be used, thus eliminating the need for extra layers of insulation and cladding.
A popular approach in industrial applications is to use two orthogonal layers of corrugated steel panels and fill the cavities with insulation material.
In combination with lean outer beams, floor-to-ceiling glazing can also be implemented.

The facade panels carry horizontal wind loads. If grid spacing is too wide, additional columns or orthogonal wall elements have to be installed to attenuate deformation.
When used as bracing element, an outer wall element must be connected to its adjacent columns with sufficient shear resistance. This is often achieved through grouting.
Wall-to-wall connections are made by cable loop systems (Figure 17). A B 500 steel rod is inserted into the cable loops, then the gaps between the walls are sealed with expanding foam or other types of sealant and the cavity is filled with grout.

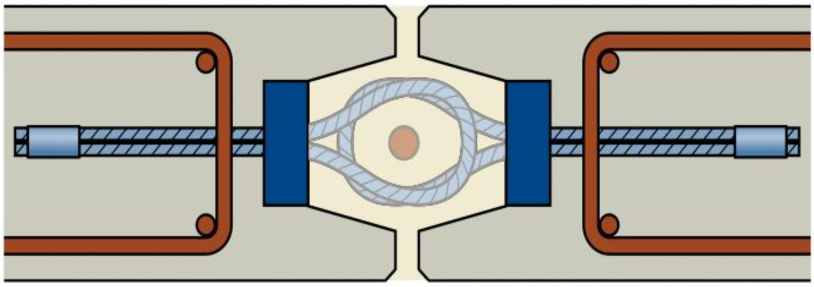


Figure 17: Cable loop connection between two precast walls
Source: Pfeifer Seil- und Hebetechnik GmbH, Memmingen

Purlins and frames
Precast purlins and frames are used in roof constructions with very high span length, such as industrial facilities. Due to the focus of this project, this subject is of secondary importance and will not be examined here any further.

2.5 Overview of prefabricated timber construction with CDW

2.5.1 Classification of timber

In Germany, timber from CDW will be classified according to the waste wood ordinance into two main groups called industrial wood waste and used wood [30]. The former group relates to residuals coming from the woodworking industry that are not directly reused or recycled and have to be disposed. The latter were formerly a product and can be separated according to their origin as e.g. construction, packing material etc. In relation to the processing state, waste timber will be assigned to the so-called wood waste categories, identifying the grade of contamination and the respective reuse or recycling opportunities.

Fields of application of recycled timber
In Germany and other European countries (par. 2.1), the recycling of materials takes mainly place in the woodworking industry for the production of chipboards and fibre boards. Although recycling rates are increasing, it has to be noted that overall the rate for material recycling of timber in Europe is relatively low and the majority of wood waste is incinerated in an unsorted way. In Germany the main reason for this situation relates to the relatively strict requirements set out in

the waste wood ordinance, which are unique in Europe and stipulate a fairly restricted use for treated, coated or laminated timber containing halogen organic compounds or wood preservation [31]. As the determination of such compounds requires technical equipment, most often the worst case scenario will be assumed and the waste material will be incinerated. For that reason, 50% - 75% of material potentially available for a cascade use is lost. In addition, the incentives for the energy production from renewable resources encourage stakeholders to deploy recycled timber to thermal use.

Based on the research carried out to date it can be established that the use of CDW in prefabricated timber elements for construction in Europe is non-existent. The reasons for this are manifold and relate to economical and technical issues, knowledge and other considerations as described above.

However, in light of an adapted European legislation, resulting in the German Waste Framework Directive, which sets out and promotes a different hierarchy of waste processing, an increase in material reuse and recycling is likely to happen in the near future, as energetic recovery is clearly considered as the last solution. In order to facilitate this change, new innovative concepts for the reuse or recycling of timber into structural elements and other applications are required. Such initiatives have to be supported by in-depth research for the direct reuse and up-cycling. The work carried out within the RE^4 project will help to minimise current knowledge gaps in research and construction and promote the use of prefabricated CDW from timber in the near future.

In the absence of any examples for prefabricated elements made from timber CDW, projects featuring a direct reuse of timber elements as well as attempts for the recycling of timber waste for construction materials or elements will be presented in the following sections. The use of recycled timber for furniture has not been included in this report, as it has been considered as irrelevant in the context of the RE^4 project.

2.5.2 Reuse of timber for structural elements

Examples for direct reuse could mainly be established for either the refurbishment of listed buildings or in regions where timber construction predominated in the past and demonstrates until today a very high cultural acceptance (Figure 18). In countries like Austria or in certain regions of Germany high grade, recycled timber is classified as a premium product, valued for their architectural appearance. In certain cases, the reuse of timber is more considered as buying antiques rather than undertaking a sustainable approach. Such projects are normally relatively small in scale (2 storeys) and are characterised through historic timber construction with reversible connections, which enables a complete dismantling of the former building without major losses of components or elements. Such components will then be used in a similar application. These findings explain why prefabrication based on recycled timber for structural purposes has not been developed yet. First of all, timber construction has significantly changed in recent years and moved from traditional handmade construction towards highly efficient prefabrication with industrialised machinery. Secondly, components available for reuse are characterised through smaller dimensions than what modern construction require nowadays. Therefore, their direct reuse in similar sized projects, where the same level of craftsmanship is required, is the most feasible option. In addition, access to forest timber is still relatively cheap, as current resources still exceed the current demand. In certain cases, the direct reuse relates only to parts of an element such as a weathering boards for a façade (Figure 19) or to the decorative use of elements (Figure 20).

In Australia, access to timber harvested from old-growth forests is strictly restricted, which implies that many species can only be purchased as used materials. In addition, waste management is improving and an enhanced dismantling of buildings achieves better-diverted materials demonstrating a higher quality. Labour intensive works such as de-nailing becomes profitable due to an increasing market for recused and recycled timber products. Also in regions around the Alps, several carpentries, specialised in historic construction reusing timber from historic buildings, have been identified.

Figure 18: Reused timber from historic building for new construction of residential building, Source: www.Altholz.net

Figure 19: Reused timber for façade cladding, Source: www.nullabortimber.a u

Figure 20: Reused timber as ceiling boards for a renovation project in Seddon, Australia, Source: www. sanctuarymagazine.org.au

2.5.3 Example of dismantling and direct reuse of a timber building

Figures from 21 to 27 show an architectural project in Bavaria, Germany, carried out by Roswag Architekten, where an old peat barn has been carefully dismantled with the aim to reuse the entire structure for a new two storey mixed used project in a different location. A new architecture for residential purposes has been integrated into the old structure, which has been dedicated to workshop spaces and a large storage for crafts materials. Due to the reversible, connections, the entire building could be taken down relatively easy and was put into storage until the client purchased a new construction site. For the reconstruction, approx. 95% of the old structure could be reused. New timber elements were used only in such locations, where historic ones did not fulfil structural requirements or were simply missing. The project demonstrates the opportunities for sustainable dismantling and reuse, based on an appropriate design. However, it has to be noted that without the clients efforts such a project would have never been realised due to economic reasons.

Figure 21: Existing peat barn in Kolbermoor, Germany, during dismantling phase.

Figure 22: Storage of single elements and components of dismantled peat barn.

Figure 23: Reconstruction of support structure (columns and beams) on new foundations.

Figure 24: Historic support structure with internal partition walls from new materials.

Figure 25: Historic façade made from timber slats and new construction.

Figure 26: Historic beam with modern metal bearing for structural support of new crossbar

Figure 27: Finalised flat at ground floor level with historic structural system and modern elements for interior fit-out

2.5.4 Construction materials or elements made from timber CDW

Materials or elements made out of timber CDW are very limited and mainly related to boards suitable for wall or furniture application, made from grinded timber waste. Applications, where the final product is a composite element, are not presented here, as their future recycling has to be evaluated further. Only in very limited cases, timber elements have been up-cycled into new elements. Figure 28 shows timber screens made from recycled material for a 10-storey high rise building and Figure 29 shows recycled timber as a 100% FSC by-product wood, manufactured as compressed wood composite panels that can be used for flooring, panelling and other wood products. Figure 30 shows a 3D recycled and recyclable composite panel, made from urban, farm and forest materials that can be used for interior wall applications etc. The product is produced with water, heat and pressure and refrains from any additives.

Figure 28: CH2 project, Melbourne, Australia : Recycled timber for façade screens of 10 storey high rise building, Source: www.nullabortimber.au

Figure 29: Songwood, compressed wood composite from recycled timber for internal partition wall application, Source: www. architectmagazine. com

Figure 30: ECOR, 3D recycled and recyclable composite panel for internal partition wall application, Source: www.ecorglobal.com

2.6 Overview of prefabricated timber construction without CDW

2.6.1 General overview

Due to its physical and mechanical properties, wood is particularly suitable for prefabrication, as it is a light material, but at the same time demonstrates excellent load-bearing capacities. In addition, it is easy to manufacture and process and offers an outstanding accuracy with regard to dimensional tolerances, so that the number of large-scale prefabricated timber constructions projects is steadily increasing.

Prefabrication reduces also error rates and weather driven construction defects, as the construction process is relocated from the construction site into a carpentry workshop and times for assembly are significantly shortened. In addition, an increased security in terms of planning reliability, quality, cost and deadline can be achieved.

Timber as a renewable resource offers great ecological potential in the construction sector. Like no other building material timber is able to buffer and store CO_2 (1t CO_2/m^3 timber) [32]. In addition, an intelligent cascade use offers significant potential to extend the materials or components lifespan through reuse, upcycling, downcycling and energetic recovery at the end of life. The limited weight but also local availability have a positive effect on transport and construction times.

Nowadays wood can be cut, bored, milled and shaped errorless with an outstanding accuracy of a tenth of a millimetre. New production methods and computational based design enable entirely new forms of design and construction and robotic system increase time and cost efficiency. An increasing number of pilot projects lead to increasing dimensions with regards to spans and height for elements but also number of storeys. Standard construction achieve nowadays spans of 10 m, whereas material properties and ambitious engineering assume that through glue laminated timber beams much larger spans are achievable [33]. Ambitious projects worldwide, currently under construction or recently finalised, exceed the limit for high-rise buildings in many cases.

2.6.2 Realised projects with prefabricated timber elements

UK

In London the first urban housing project was constructed in 2009 entirely from pre-fabricated solid CLT timber as a 9-storey (30 m) building, with load bearing walls, floor slabs, stairs and lift cores.

Canada, British Columbia

In Vancouver (Canada) an 18-storey (53 m) solid timber construction as student housing will be finalised in 2017. Just as in London, all elements are made from timber. Due to strict fire protection regulations, timber elements are capsulated in addition to a sprinkler system that had to be installed. Construction cost for the entire building were approx. 3 Mio EUR higher in comparison to steel or concrete. However, the steadily increasing number of pilot projects in combination with applied research gives reason to expect that construction cost for timber construction can significantly be reduced in the near future.

Austria

In Vienna (Austria), a 24-storey timber construction has started in 2016. Due to the high degree of prefabrication, the concrete timber hybrid construction of the 9-storey life cycle tower one in Dornbirn (Austria) has been erected in only two weeks. The project is considered as prototype for hybrid construction as it has been developed as a building system ready for installation. An important step for timber construction with regard to fire protection has been realised through in-depth fire testing of a number of concrete timber hybrid ceiling elements (2.7 m x 8.1 m). The fire protection authority granted a test certificate according to DIN EN 13501 for fire resistance REI 90 of the wood composite cover (Figure 31).

Norway

In Trondheim (Norway), a student-housing scheme with several 9-storey towers has recently been finalised (2015 – 2016). Apart from the foundations and the ground floor level all other storeys have been constructed in cross-laminated timber (CLT) with visible elements, where possible (Figure 32).

Germany and Switzerland
In Germany the first 8-storey mixed used (office and residential) has been erected in Bad Aibling. In Switzerland, several 6-7 storey buildings have been arisen.

Italy
In Italy high-rise building limit does not exist, which should make planning approval much easier.

Figure 31: : Life Cycle Tower One, Dornbirn, timber hybrid construction

Figure 32: Moholt 50 / 50, Norway, CLT construction

2.6.3 Limitations for prefabricated timber construction

Modern timber construction has overcome limitations of traditional timber construction, which were characterised through the craftsmanship and dimensions of naturally grown trees. Through the development of glue and cross-laminated (CLT) new construction system with far larger spans are possible. Construction laws or economical considerations, not material properties itself, are nowadays the limiting factors. For the height of elements 3 m is currently the limit as higher elements require special trucks and transport permits. The length of a construction element, again, is informed by current limitation due to transport. Due to the material properties, weight is less important with regard to transport.

Constructional research in recent years achieved significant improvements with regard to fire, thermal and noise protection and seismic design so that a steady increase of prefabricated timber construction can be determined. However, standards relate to state of the art construction of the past and lag behind current development. In addition, the tremendous number of requirements and regulations are complicating the design and construction process unnecessarily, so that simplification through additional research and application related material development is urgently required to exploit the materials' full potential. Considering reinforced concrete prefabricated construction, even though reinforced concrete has been studied and developed for decades, certain types of construction still need individual case approval.

2.6.4 Timber Construction

Timber construction can be divided into massive construction, based on solid wood and skeleton construction, where also engineered wood is applied. Prefabrication has been established for both construction methods. In the following sections, different solutions for both types will be presented in greater detail.

Timber frame construction (Skeleton construction)
The basic principle of the construction consists of a structural wooden frame divided into horizontal wooden sleeper, plate and vertical pole and a corresponding panelling. Vertical loads will be transferred through poles, whereas bracing of the supporting structure is achieved through the application of covering boards.

The slim, high cross sections of the frames require a narrow support spacing, positioned according to a grid of normally 62.5 cm and filled with insulation material such as flakes, fibres or mats. Standard construction materials (structural solid timber or laminated timber) and standardised principals, leading to fairly repetitive connection details, make the construction very time and cost efficient. Since the introduction of this construction the width of the timber poles remained constantly 60 mm [34]. Elements dimensions follow the dimension of the covering boards. Nevertheless timber frame constructions offer a high degree of flexibility and can easily be adapted to existing conditions and user requirements. Different options for covering boards in relation to different requirements (constructive, thermal, structural) or aspirational (aesthetics) such as OSB, wood fibre or gypsum plaster or other boards approved for building installation can be used. Current state of the art is vapour permeable construction with the structural board being located towards the inside of the panel, functioning as air tightening layer for the element.

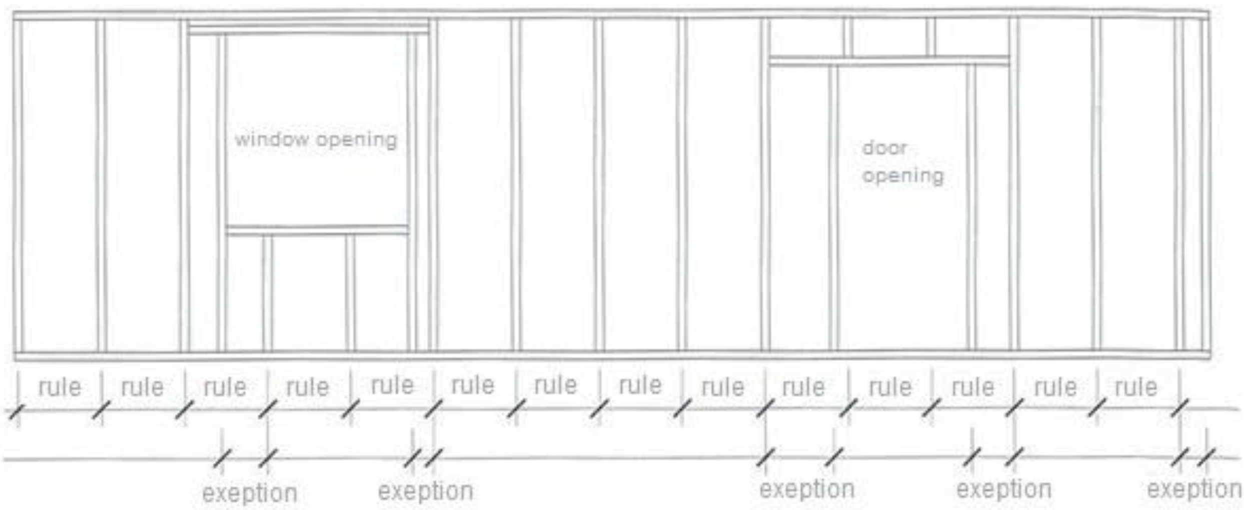


Figure 33: Timber frame construction with openings from basic grid, Source: Peter Cheret u.a. Holzbau Handbuch Reihe 1, Teil 1 Folge 7, Holzrahmenbau, S. 26

The position of windows, door openings and internal partition walls can be arranged according to the project's needs. Figure 33 shows the principal of a timber frame construction based on a defined grid, with exceptions for window and door openings. Figures 34 and 35 show the prefabrication of a façade element in the workshop. Usually, timber frame constructions are erected storey-wise. Figure 36 and Figure 37 show the transport and assembly of timber frame panels.

Figure 34: Prefabrication of timber frame elements in the workshop, Source: Benedikt Wagner, Holzbau Schenk GmbH

Figure 35: Turning table for easy assembly of timber frame in the workshop, Source: Randek AB

Figure 36: Transport of timber frame element, Source: Benedikt Wagner, Holzbau Schenk GmbH

Figure 37: Assembly of timber frame element, Source: Frank Schäfer, 2-box Architekten

Timber panel construction (Skeleton construction)

Timber panel construction is based on the same construction principal as the timber frame construction, but differs with regard to the level of prefabrication. Usually for timber panel construction, the elements are industrially fully finalised and include all surfaces, windows and installations. In case of closed elements an independent quality control through certified auditors is required in addition to self organised factory monitoring.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

For both constructions the different elements (wall, ceiling, and roof) are regulated according to DIN 1052 Design, calculation and dimensioning of timber structures.

Massive construction

In modern, solid timber construction, the industrialised timber product functions as load bearing and space creating element at the same time and can be applied as wall-, ceiling- and roof panels, due to their very large dimensions. Laminated timber, glue laminated timber (glulam) and cross laminated timber (CLT / X-Lam) are industrially made wooden elements (Figure 38– Figure 40). Laminated timber and BSH wood consists of at least three timber boards or slats that are joined together parallel in direction of growths. Laminated timber, which is joined with either nails, screws or wooden dowels, has nowadays largely been replaced by BSH, where single layers are glued together. CLT in comparison is a massive and flat wooden product, where at least three layers of trimmed timber are glued at right angles to each other. For the first time in the history of timber construction, wood is applied as a flat, undirected building material and not as a rod shaped, directed component. The load bearing capacity of all three products is up to 50% higher than that of lumber, which explains its growing application.

Figure 38: Stacked timber with dowels

Figure 39: Glue laminated Timber (glulam)

Figure 40: Cross laminated timber (CLT / X-Lam)

Amongst these three main types of products presented above, different variations exist on the market. Dimensions of different products for CLT and glue laminated timber are presented in Table 10. As mentioned before, they are suitable for application as wall/façade -, ceiling - or roof element.

	Product Name	**Thickness**	**Width**	**Length**	**Type of wood**
Cross laminated timber	CLT	up to 400 mm	2.95 m – 4.00 m	16 m	Spruce
	GFP Large format panel	27 mm – 500 mm	up to 4.00 m	13.7 m	Not specified
	KLH	up to 500 mm	2.95 m	16.5 m	Spruce

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

	Product Name	Thickness	Width	Length	Type of wood
Glue laminated timber	Glulam	80 mm – 220 mm	0.52 m – 1.20 m	16.0 m	Not specified
	Stacked element	60 mm – 260 mm	0.12 m – 1.00 m	30.0 m	Not specified
	Bloc timber	tbc	up to 0.60 m	9.0 m	Spruce, pine, larch, douglas

Table 10: CLT and glue laminated timber products and their specific dimensions

2.6.5 Prefabricated timber elements

Columns

Prefabricated timber columns are generally made out of solid timber, either from one stem (Figure 41) or in case of larger dimensions of glued profiles (Figure 42). Their dimensions depend on the project specific parameters, such as:

– load cases (number of storeys, spans, live load, bearing)
– building typology (use classes etc.)
– building classes (German system in relation to building height and footprint)
– strength class of timber
– requirements with regard to fire protection

Figure 41: Solid timber column from one stem

Figure 42: Solid timber column from BSH timber

In general, columns are rectangular in line with the structural support system. Their connection to floor or ceiling can be constructed in different ways in relation to the required bearing. Market solutions range from steel fittings that are integrated into the timber to scenarios where the column itself is grouted in case of concrete flooring with the latter options being less suitable for dismantling.

Beams

Similar to columns, prefabricated timber beams are made out of solid timber either from one stem or in case of larger dimensions of glued profiles (Figure 43). In case of reduced load cases, several solutions are available on the market such as web beams (Figure 44) that aim to optimise the material consumption. As with for columns, their dimensions depend on the project specific parameters, such as:

- load cases (number of storeys, spans, live load, bearing)
- building typology (use classes etc.)
- building classes (German system in relation to building height and footprint)
- strength class of timber
- requirements with regard to fire protection

Figure 43: Solid timber beam from BSH

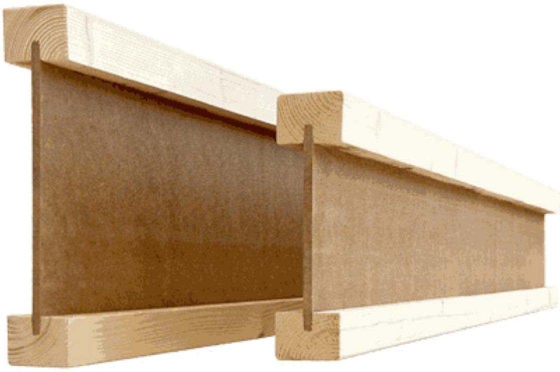


Figure 44: Timber beam with solid timber flanges and a web from hard fibre boards

Floor, ceiling and roof elements

For timber construction, the following three different types of ceiling systems exist currently on the market.

- solid timber ceiling
- timber frame ceiling
- timber concrete hybrid ceiling.

As timber concrete hybrid construction is not relevant for the RE^4 project only the first two systems will be presented in greater detail. The dimensions of a ceiling depend on the project specific parameters, such as:

- ceiling construction
- load cases (number of storeys, spans, live load, bearing)

– building typology (use classes etc.)
– building classes (German system in relation to building height and footprint)
– strength class of timber
– requirements with regard to fire protection
– requirements with regard to noise protection
– airtightness (In Germany to be evidenced per flat)
– requirements with regard to thermal protection (less important)

Economic spans for solid timber ceilings go up to 6 m, whereas for timber frame ceilings they start at 6 m.

Solid timber ceiling
Solid wood ceilings are characterized through limited thicknesses and good fire resistance and simple connection details. During construction, the element can immediately be accessed. Their biggest drawback is the relatively high material consumption.

Solid ceiling systems are subdivided into systems with a linear and a two dimensional load-bearing behaviour. The linear systems include the solid wood beam (Figure 45), raftered decks and glue laminated ceilings (Figure 46), whereas CLT (Figure 47), laminated veneer lumber or multilayer boards are classified as two dimensional systems, which enable an easy diaphragmatic formation.


Figure 45: Solid timber ceiling from wood beams


Figure 46: Solid timber ceiling as BSH element


Figure 47: Solid timber ceiling as CLT element

Timber frame ceiling
The wooden frame ceilings are divided into ribbed slab and hollow box ceiling (Figure 48). In both systems, the two-dimensional planking belongs to the structural system. In case of the ribbed slab, this connection takes place only on one side (either top or bottom), whereas for the hollow box ceiling it's on both sides. The advantages of these systems are their reduced weight, immediate access and limited material usage. The system is suitable for medium to large size spans.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 723583

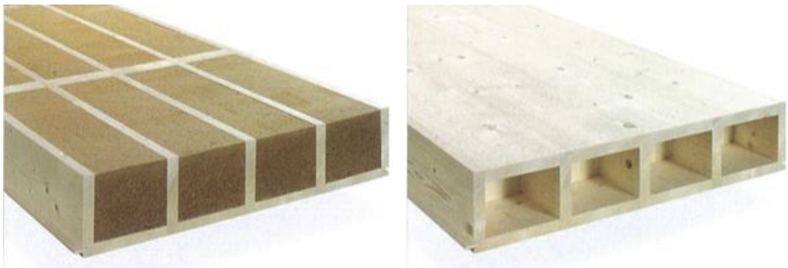


Figure 48: Solid timber ceiling from wood beams

Figure 49: Assembly of ceiling element

2.6.6 Connection Details

The connection details impact significantly on the feasibility, durability, thermal, hygrothermal and fire protection but also on reuse or recycling. DIN 68800-2:2012-02 Timber protection Part 2: Preventive constructive measures provides different options for detail and component connections as well as the integration of installations. In combination with testing certificates, such details can be classified as highly fire retardant or fire resistant [35]. Current connections are mainly based on metal fittings such as nail plates, which are not suitable for a sustainable dismantling. In the framework of the RE^4 project more suitable connection means shall be developed.

2.7 LCA and LCC impact of conventional construction versus prefabrication

Economic and environmental performance of concrete buildings varies a lot between different buildings in EU. The main reasons are: a) regional differences in building design and production, b) differences in concrete mix design, c) differences use of pozzolanes as binders, d) differences in competitions between entrepreneurs, e) regional differences in electricity mix and f) differences in climate conditions. In this study, as a preliminary reference building, assemblies data are used from Swedish conditions.

2.7.1 Life Cycle Assessment, LCA, of building assemblies

The core standards ISO 14040:2006[36] and ISO 14044:2006 [37] and ILCD [38] for LCA are followed. Methodology for LCA for building constructions has been developed by the European standardization organization CEN. In this project both ILCD and CEN standard is followed but in some case CEN provide a more transparent documentation (i.e. the module system) that is essential for a research project. The standard provided for environmental performance for building products by CEN TC350, Sustainability for construction works is EN 15804:2012+A1:2013[39]

Environmental indicators

The project is focused on recycling of construction and demolition waste, CDW. Qualitative and quantitative rates of recycled content are the most important indicators. Mass flow is expressed as flow of material in kg and recycled amount in percentage, e.g. 5 kg mineral wool with 82% recycled content are expressed as 5:82.

The other indicators are the five main indicators specified in EN 15804.

Global Warming (GWP 100)	kg CO_2-eq.
Ozone depletion (ODP)	kg R_{11}-eq.
Acidification (AP)	kg SO_2-eq.
Eutrophication (EP)	kg PO_4-eq.
Photochemical ozone creation (POCP)	kg C_2H_4-eq.

Table 11: Environmental indicators

Service life

Concrete is a very durable material. Without any knowledge of physical and chemical properties of cement and concrete it was possible to build 2000 years' service life and today we can see buildings in Rome like pantheon that still stand in its full beautifulness. Today the concrete technology has developed a lot and it's possible to build far more durable buildings. But in an expanding linear economy in a rapid changing world there have not been any demand of this magnitude of service life. The attempt to introduce resource effective strategies for minimizing waste streams could perhaps create a demand on longer service life. Long-time destruction processes for concrete could primary be explained by reinforcement corrosion. This is not a problem for Pantheon because the dome construction has pressure forces and do not need reinforcement.

When we look at a modern building, we can see that all interior walls have also compressive forces. In addition, all interior slabs in a modern building is in a dry environment were corrosion could not occur. We set the service life to 100 years. It is much less than economical and technical possible but in the higher end related to common used service life for buildings. However, we can assume that all interior concrete elements could be reused for new buildings if they fulfil the geometric properties for the new building and could easily be deconstructed.

System boundaries

The system boundaries for the reference building assemblies are from cradle (i.e. virgin or waste materials) to grave (i.e. reusable waste materials). The system boundaries are described by Figure 50 (EN 15804). In the inventory of reference assemblies, environmental impacts are inventoried in A1-A5, B1, B4, C1-C3.

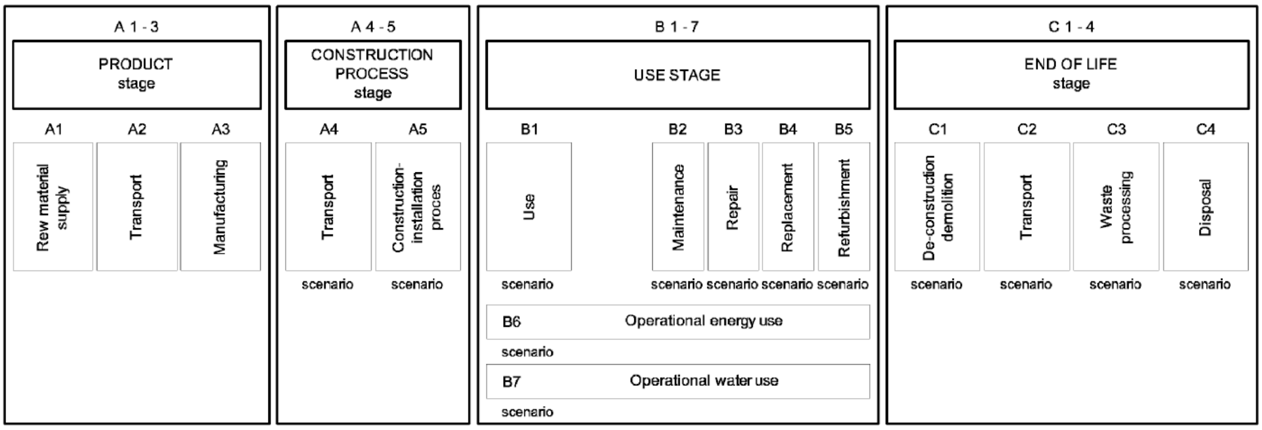


Figure 50: System boundaries and modules

– A1 includes raw material production like cement production and concrete additives production and for the prefabricated concrete also the fastening products;
– A2 includes transport of materials to the concrete factory;
– A3 includes environmental impact on the concrete factory. Mostly comes from energy used. For the ready mixed concrete, A3 also includes the impact from production of insulation and reinforcement;
– A4 includes transport of building products to the building site;
– A5 includes impact from construction of the building onsite. The impact is mainly due to the energy used.
– B1 includes carbonation of concrete during the use stage;
– B4 includes two replacement of façade mortal for the ready mixed walls;
– C1 includes demolition of the building;
– C2 includes transport of demolished waste to treatment facility;
– C3 includes crushing and sieving concrete waste to produce new materials, such as aggregates for new concrete. Energy for size reduction of concrete is estimated from size reduction of stone. The processes are first a jaw crusher (0,4 kWh/ton) and then a gyratory crusher (0,5 kWh/ton). Sieving uses approximately 0,34 kWh/ton and conveyor belts 0,5 kWh/ton. It is estimated that approximately 1,74 kWh electricity/ton concrete of energy is requested for this phase.

Building assemblies

The studied building assemblies (Table 12) are precast and ready mixed concrete facades, interior walls and floors for residential and office buildings.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

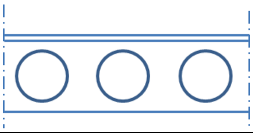
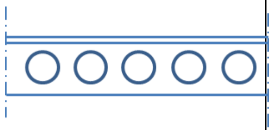
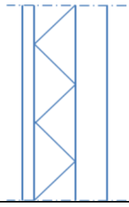
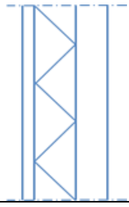
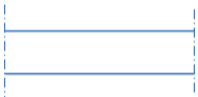
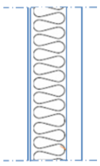
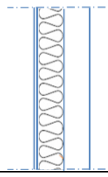
Precast concrete			
Residential building		**Office building**	
Floor 10 mm Levelling mortar 265 mm Hollow core slab 5,2 kg/m^2 Pre stressed reinforcement	**O** 	**Floor** 10 mm Levelling mortar 200 mm Hollow core slab 3,9 kg/m^2 Pre stressed reinforcement	**P** 
Facade 60 mm concrete 1,5 kg/m^2 reinforcement 250 mm EPS 150 mm concrete 1,5 kg/m^2 reinforcement	**Q** 	**Facade** 60 mm concrete 1,5 kg/m^2 reinforcement 150 mm EPS 150 mm concrete 1,5 kg/m^2 reinforcement	**R** 
Interior load bearing wall 200 mm concrete 6 kg/m^2 reinforcement	**S** 	**Interior load bearing wall** 200 mm concrete 6 kg/m^2 reinforcement	**S** 
Ready mixed concrete			
Residential		**Office building**	
Floor 200 mm Concrete 7,1 kg /m^2 reinforcement	**T1** 	**Floor** 230 mm Concrete 15,3 kg /m^2 reinforcement	**T2** 
Facade 10 mm mortar 220 mm Mineral wool λ=0,033 150 mm Concrete 1,5 kg /m^2 reinforcement	**U** 	**Facade** 10 mm mortar 160 mm Mineral wool λ=0,033 150 mm Concrete 1,5 kg /m^2 reinforcement	**V** 
Interior load bearing wall 200 mm concrete 6 kg/m^2 reinforcement	**X** 	**Interior load bearing wall** 200 mm concrete 6 kg/m^2 reinforcement	**X** 

Table 12: Building assemblies

Surface material assumed in CO2-uptake assessment

In the LCA analysis the impact from surface materials (e.g. paint, etc., Table 13) are not included. However, for the calculations of CO_2 uptake by carbonation of concrete parts during the use phase, the surface materials are considered to act as a barrier.

	Side 1 (inside or upside)	Side 2
Floor	linoleum	paint
Sandwich facade	Paint	--
Ready mixed concrete facade	Paint	Free
Interior load bearing wall	Paint	Paint

Table 13: Surface material

Data examples for modules A-C (i.e. construction process, use and end of life stages) are given in Table 14.

	A4	A5	B1	B4	C1	C2	C3
Prefabricated concrete							
Floor	100 km lorry	9 kWh/m^2 Electricity	Carbonation	------	10,4 MJ/m^2 Diesel	30 km lorry	1,74 kwh/ton Electricity
Floor Office	100 km lorry	6,88 kWh/m^2 Electricity	Carbonation	------	8 MJ Diesel	30 km lorry	1,74 kwh/ton Electricity
Facade	100 km lorry	12,8 kWh/m^2 Electricity	Carbonation	------	14,9 MJ Diesel	30 km lorry	1,74 kwh/ton Electricity
Façade Office	100 km lorry	12,8 kWh/m^2 Electricity	Carbonation	------	14,8 MJ Diesel	30 km lorry	1,74 kwh/ton Electricity
Interior wall	100 km lorry	10,11 kWh/m^2 Electricity 36,4 MJ/m^2 Diesel	Carbonation	------	33,36 MJ Diesel	30 km lorry	1,74 kwh/ton Electricity
Ready mixed concrete							
Floor	30 km concrete mixer truck, Reinforcement 150 km lorry	9,75 kWh/m^2 Electricity 35,1 MJ/m^2 Diesel	Carbonation	------	32,1 MJ/m^2 Diesel	30 km lorry	1,74 kwh/ton Electricity
Floor	30 km concrete mixer truck, Reinforcement 150 km lorry	11,4 kWh/m^2 Electricity 41,4 MJ Diesel	Carbonation	------	37,5 MJ/m^2 Diesel	30 km lorry	1,74 kwh/ton Electricity
Façade	30 km concrete mixer truck, Reinforcement 150 km lorry	7,64 kWh/m^2 Electricity 27,7 MJ/m^2 Diesel	Carbonation	2 changes of plaster	25,2 MJ Diesel	30 km lorry	1,74 kwh/ton Electricity
Façade Office	30 km concrete mixer truck, Reinforcement 150 km lorry	7,6 kWh/m^2 Electricity 27,5 MJ/m^2 Diesel	Carbonation	2 changes of plaster	25,2 MJ Diesel	30 km lorry	1,74 kwh/ton Electricity

Interior wall	30 km concrete mixer truck, Reinforcement 150 km lorry	9,75 kWh/m^2 Electricity 35,1 MJ/m^2 Diesel	Carbonation	------	32,1 MJ/m^2 Diesel	30 km lorry	1,74 kwh/ton Electricity

Table 14: Example Input data in the analysis

Functional unit

Building components are only comparable if they have the same functional unit. The functional unit, for the building components, is described by primary function (impact/ m^2, 100 year) that is the same for all building assembles; moreover, also additional functions (i.e. thermal performance, fire resistance, exposer class, etc.) are the same for equal assemblies as reported in Table 15.

Building assembly	Service life	U-value	Sound class	Fire class	Span	Concrete Exposer class
Prefabricated concrete						
O, Floor	100	-----	B	R90	13,7 single tense Simply supported	XC1
P, Floor, Office	100	-----	B	R90	8,6 single tense Simply supported	XC1
Q, Facade	100	0,15	B	R90	-----	XF1, XC4
R, Façade Office	100	0,20	B	R90	-----	XF1, XC4
S Interior Wall	100	-----	B	R90	-----	XC1
Ready mixed concrete						
T1, Floor	100	-----	B	R90	9,7 single tense elastic, continues	XC1
T2, Floor Office	100	-----	B	R90	10,5 Pillar deck	XC1
U, Facade	100	0,15	B	R90	-----	XC1
V, Façade, Office	100	0,20	B	R90	-----	XC1
X, Interior Wall	100	-----	B	R90	-----	XC1

Table 15: Additional functional units

Beside the functional units for the building assemblies, there are two important functions for concrete mix design that often are desired by the producers of prefabricated concrete blocks.

– Early strength for fast production and de-mould after 8 hours.
– Self-compacting concrete to allow fast production, good filling of the mould and minimize a heavy work with occupational health risks.

Impact assessment

For each building assembly (Table 12) and for each life cycle phase (Figure 50) the potential environmental impact, considering the indicators described in Table 11, is reported. The following information is also included:

– % recycle content for reinforcement, cement, mortar materials is indicated (Module A);
– Potential reuse and recycling (a, b and c alternatives) of concrete, cement, mortar materials is indicated (Module C2, C3).

1) Precast concrete

O, Floor, residential building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	+359,3							-359,3:100a	
Concrete: recycled part	kg: %	+337,1:--								-337,1:100b
Reinforcement: recycled part	kg: %	+5,2:100							-5,2:100c	
Cement:recycled part	kg: %	+50,5:12,4								
Leveling mortar:recycled part	kg: %	+17:0							-17:100b	
Global Warming (GWP 100)	kg CO2-ekv.	4,4E+01	1,3E+00	6,4E-01	2,0E+00	5,0E-01	-1,8E+00	8,3E-01	6,0E-01	3,5E-02
Ozon depletion (ODP)	kg R11-ekv.	6,72E-07	8,80E-07	3,15E-07	1,55E-07	4,62E-07		6,119E-08	4,66E-08	3,2089E-08
Acidification (AP)	kg SO2-ekv.	6,07E-02	1,84E-02	7,82E-03	8,09E-03	1,95E-03		0,0018951	0,00242728	0,00013557
Eutrophication (EP)	kg PO4-ekv.	2,84E-02	1,94E-03	3,24E-03	1,44E-03	7,76E-04		0,0003304	0,00043154	5,3875E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	8,49E-03	5,42E-04	6,66E-04	1,12E-04	1,19E-04		4,702E-05	3,3657E-05	8,2399E-06

Table 16: Environmental impact from assembly O

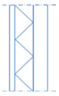
a) Possible reused b) Possible recycled as aggregates c) Possible recycled to reinforcement

P, Floor office building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	+275,3							275,3:100a	
Concrete: recycled part	kg: %	+254,4:--								-254,4:100b
Reinforcement: recycled part	kg: %	+3,9:12,4							-3,9:100c	
Cement:recycled part	kg: %	+38,1:12,4								
Leveling mortar:recycled part	kg: %	+17:0							-17:100b	
Global Warming (GWP 100)	kg CO2-ekv.	3,5E+01	1,1E+00	4,8E-01	1,5E+00	3,8E-01	-1,8E+00	6,4E-01	4,6E-01	2,7E-02
Ozon depletion (ODP)	kg R11-ekv.	6,1E-07	8,6E-07	2,4E-07	1,2E-07	3,5E-07		4,7E-08	3,6E-08	2,5E-08
Acidification (AP)	kg SO2-ekv.	4,7E-02	1,4E-02	5,9E-03	6,2E-03	1,5E-03		1,5E-03	1,9E-03	1,0E-04
Eutrophication (EP)	kg PO4-ekv.	2,6E-02	1,5E-03	2,5E-03	1,1E-03	5,9E-04		2,5E-04	3,3E-04	4,1E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	7,1E-03	4,3E-04	5,0E-04	8,6E-05	9,1E-05		3,6E-05	2,6E-05	6,3E-06

Table 17: Environmental impact from assembly P

a) Possible reused b) Possible recycled as aggregates c) Possible recycled to reinforcement

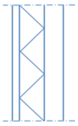


Q, Façade residential building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	+512							-512:100 a	
Concrete: recycled part	kg: %	+505,5:--								505,5:100b
Reinforcement: recycled part	kg: %	+1,5:100							-1,5:100c	
Cement:recycled part	kg: %	+75,6:12,4								
EPS:recycled part	kg: %	+5:0							-5:0	
Global Warming (GWP 100)	kg CO2-ekv.	5,9E+01	1,5E+00	2,5E+00	2,5E+00	7,1E-01	-4,6E+00	1,2E+00	7,6E-01	5,0E-02
Ozon depletion (ODP)	kg R11-ekv.	3,3E-07	2,1E-07	9,7E-07	2,0E-07	6,6E-07		8,8E-08	5,9E-08	4,6E-08
Acidification (AP)	kg SO2-ekv.	7,8E-02	1,1E-02	9,5E-03	1,0E-02	2,8E-03		2,7E-03	3,1E-03	1,9E-04
Eutrophication (EP)	kg PO4-ekv.	1,3E-02	1,4E-03	2,3E-03	1,8E-03	1,1E-03		4,7E-04	5,5E-04	7,7E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	6,5E-02	2,4E-04	3,9E-04	1,4E-04	1,7E-04		6,7E-05	4,3E-05	1,2E-05

Table 18: Environmental impact from assembly Q

a) Possible reused b) Possible recycled as aggregates c) Possible recycled to reinforcement



R, Façade office building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	+510,75							- 510,75:100a	
Concrete: recycled part	kg: %	+504:--								-504:100b
Reinforcement: recycled part	kg: %	+1,5:100							-1,5:100c	
Cement:recycled part	kg: %	+75,6:12,4								
EPS:recycled part	kg: %	+3,75:0							-3,75:0	
Global Warming (GWP 100)	kg CO2-ekv.	5,6E+01	1,5E+00	2,5E+00	2,5E+00	7,1E-01	-4,6E+00	1,2E+00	7,6E-01	0,05
Ozon depletion (ODP)	kg R11-ekv.	3,0E-07	2,0E-07	9,7E-07	2,0E-07	6,6E-07		8,7E-08	5,9E-08	4,56E-08
Acidification (AP)	kg SO2-ekv.	7,1E-02	1,1E-02	9,5E-03	1,0E-02	2,8E-03		2,7E-03	3,1E-03	0,00019272
Eutrophication (EP)	kg PO4-ekv.	1,2E-02	1,4E-03	2,3E-03	1,8E-03	1,1E-03		4,7E-04	5,4E-04	7,6583E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	5,0E-02	2,4E-04	3,9E-04	1,4E-04	1,7E-04		6,7E-05	4,2E-05	1,1713E-05

Table 19: Environmental impact from assembly R

a) Possible reused b) Possible recycled as aggregates c) Possible recycled to reinforcement

S, Interior load bearing wall

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	+505,5							-505,5:100a	
Concrete: recycled part	kg: %	+504:--								-504:100b
Reinforcement: recycled part	kg: %	+1,5:100							-1,5:100c	
Cement:recycled part	kg: %	+72:12,4								
Global Warming (GWP 100)	kg CO2-ekv.	5,1E+01	1,5E+00	2,6E+00	2,7E+00	7,0E-01	-6,0E+00	1,2E+00	8,0E-01	0,05
Ozon depletion (ODP)	kg R11-ekv.	2,7E-07	1,6E-07	1,0E-06	2,1E-07	6,5E-07		8,6E-08	6,2E-08	4,51E-08
Acidification (AP)	kg SO2-ekv.	5,6E-02	1,1E-02	1,0E-02	1,1E-02	2,7E-03		2,7E-03	3,2E-03	0,000191
Eutrophication (EP)	kg PO4-ekv.	1,0E-02	1,5E-03	2,4E-03	1,9E-03	1,1E-03		4,7E-04	5,7E-04	7,58E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	7,4E-03	2,4E-04	4,1E-04	1,5E-04	1,7E-04		6,6E-05	4,5E-05	1,16E-05

Table 20: Environmental impact from assembly S

a) Possible reused b) Possible recycled as aggregates c) Possible recycled to reinforcement

2) Ready mixed concrete

T1, Floor residential building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	487,1							-487,1	
Concrete flow: recycled part	kg: %	480								-480: 100b
Reinforcement flow: recycled part	kg: %	+7,1: 100							-7,1:100 c	
Cement flow:recycled part	kg: %	+61: 12,4								
Global Warming (GWP 100)	kg CO2-ekv.	4,4E+01	1,2E+00	2,0E-01	9,9E-02	3,4E+00	-2,6E+00	2,6E+00	7,9E-01	4,7E-02
Ozon depletion (ODP)	kg R11-ekv.	3,8E-07	1,0E-07	1,3E-07	1,3E-15	7,1E-07		1,9E-07	6,1E-08	4,4E-08
Acidification (AP)	kg SO2-ekv.	5,3E-02	1,0E-02	1,1E-03	9,1E-07	8,5E-03		5,8E-03	3,2E-03	1,8E-04
Eutrophication (EP)	kg PO4-ekv.	1,0E-02	1,3E-03	4,2E-04	2,8E-08	2,0E-03		1,0E-03	5,7E-04	7,3E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv	6,6E-03	2,4E-04	8,9E-05	3,1E-10	2,9E-04		1,5E-04	4,4E-05	1,1E-05

Table 21: Environmental impact from assembly T1

b) Possible recycled as aggregates c) Possible recycled to reinforcement

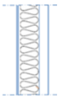
T2, Floor office building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	567,4							567,4	
Concrete flow: recycled part	kg: %	+552								-552: 100 b
Reinforcement flow: recycled part	kg: %	+15,4: 100							-15,4:100 c	
Cement flow:recycled part	kg: %	+70,1: 12,4								
Global Warming (GWP 100)	kg CO2-ekv.	5,4E+01	1,3E+00	2,3E-01	2,1E+00	4,0E+00	-2,6E+00	3,0E+00	9,2E-01	5,5E-02
Ozon depletion (ODP)	kg R11-ekv.	5,8E-07	1,2E-07	1,5E-07	3,4E-07	8,3E-07		2,2E-07	7,1E-08	5,1E-08
Acidification (AP)	kg SO2-ekv.	7,1E-02	1,2E-02	1,3E-03	5,0E-03	1,0E-02		6,8E-03	3,7E-03	2,1E-04
Eutrophication (EP)	kg PO4-ekv.	1,3E-02	1,5E-03	4,8E-04	8,7E-04	2,3E-03		1,2E-03	6,6E-04	8,5E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	8,9E-03	2,8E-04	1,0E-04	1,2E-04	3,4E-04		1,7E-04	5,2E-05	1,3E-05

Table 22: Environmental impact from assembly T2

b) Possible recycled as aggregates c) Possible recycled to reinforcement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

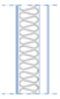


U, Façade residential building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	B4 Replacement	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	+382,05								-382,05	
Concrete: recycled part	kg: %	+360:--									-360: 100b
Reinforcement: recycled part	kg: %	+1,5: 100								-1,5:100 c	
Cement:recycled part	kg: %	+51: 12,4									
Mineral Wool: recycled part	kg: %	+2,72:82								-2,72:0	
Mortal: recycled part	kg: %	+17:0						+34 (-34):-- e		-17:100b	
Global Warming (GWP 100)	kg CO2-ekv.	4,3E+01	7,2E-01	1,5E-01	1,3E+00	2,6E+00	-2,9E+00	6,0E+00	2,0E+00	6,2E-01	3,70E-02
Ozon depletion (ODP)	kg R11-ekv.	5,8E-07	7,8E-08	9,7E-08	2,2E-07	5,6E-07		1,4E-07	1,5E-07	4,8E-08	3,41E-08
Acidification (AP)	kg SO2-ekv.	6,2E-02	1,4E-02	8,4E-04	3,1E-03	6,7E-03		4,3E-03	4,6E-03	2,5E-03	1,44E-04
Eutrophication (EP)	kg PO4-ekv.	1,2E-02	1,3E-03	3,1E-04	5,3E-04	1,5E-03		1,7E-03	8,0E-04	4,5E-04	5,73E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	1,1E-02	3,7E-04	6,7E-05	7,5E-05	2,3E-04		1,0E-02	1,1E-04	3,5E-05	8,76E-06

Table 23: Environmental impact from assembly U

b) Possible recycled as aggregates c) Possible recycled to reinforcement



V, Façade office building

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	B4 Replacement	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	381,22								-381,22	
Concrete flow: recycled part	kg: %	+360:--									-360: 100b
Reinforcement flow: recycled part	kg: %	+1,5: 100								-1,5:100 c	
Cement flow:recycled part	kg: %	+51: 12,4									
Mineral wool: recycled part	kg: %	+2,72:82								-2,72:0	
Mortal: recycled part	kg: %	+17:0						+34 (-34):-- e		-17:100 b	
Global Warming (GWP 100)	kg CO2-ekv.	4,2E+01	7,2E-01	1,5E-01	1,3E+00	2,6E+00	-2,9E+00	6,0E+00	2,0E+00	6,3E-01	3,7E-02
Ozon depletion (ODP)	kg R11-ekv.	5,1E-07	7,8E-08	9,7E-08	2,2E-07	5,5E-07		1,4E-07	1,5E-07	4,9E-08	3,4E-08
Acidification (AP)	kg SO2-ekv.	5,7E-02	1,4E-02	8,4E-04	3,1E-03	6,7E-03		4,3E-03	4,6E-03	2,5E-03	1,4E-04
Eutrophication (EP)	kg PO4-ekv.	1,1E-02	1,3E-03	3,1E-04	5,3E-04	1,5E-03		1,7E-03	8,0E-04	4,5E-04	5,7E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	1,1E-02	3,7E-04	6,7E-05	7,5E-05	2,2E-04		1,0E-02	1,1E-04	3,5E-05	8,7E-06

Table 24: Environmental impact from assembly V

b) Possible recycled as aggregates c) Possible recycled to reinforcement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

X, Interior load bearing wall

		A1 Production of building materials	A2 Transports of building materials	A3 Manufacturing building product	A4 Transport	A5 Construction	B1 Use	C1 Decon-struction	C2 Transport	C3 Waste processing
Total material flow	kg	486							-486	
Concrete flow: recycled part	kg: %	480								-480: 100 b
Reinforcement flow: recycled part	kg: %	+6: 100							-6:100 c	
Cement flow:recycled part	kg: %	+72: 12,4								
Global Warming (GWP 100)	kg CO2-ekv.	4,4E+01	1,2E+00	2,0E-01	1,7E+00	3,4E+00	-5,1E+00	2,6E+00	7,9E-01	4,7E-02
Ozon depletion (ODP)	kg R11-ekv.	3,8E-07	1,0E-07	1,3E-07	2,9E-07	7,1E-07		1,9E-07	6,1E-08	4,3E-08
Acidification (AP)	kg SO2-ekv.	5,3E-02	1,0E-02	1,1E-03	4,0E-03	8,5E-03		5,8E-03	3,2E-03	1,8E-04
Eutrophication (EP)	kg PO4-ekv.	1,0E-02	1,3E-03	4,2E-04	7,0E-04	2,0E-03		1,0E-03	5,7E-04	7,3E-05
Phochemical oxidant creation (POCP)	kg C2H4-ekv.	6,6E-03	2,4E-04	8,9E-05	9,7E-05	2,9E-04		1,5E-04	4,4E-05	1,1E-05

Table 25: Environmental impact from assembly X
b) Possible recycled as aggregates c) Possible recycled to reinforcement

Environmental comparison ready-mixed concrete versus prefabricated concrete
From the data presented above and from long experience with environmental calculations at the Swedish concrete, the conclusions are:
Difference in environmental performance between the two types of technology is much smaller than the variations in each technology. The Key parameters are:
– Mix design
– Type of cement
– Use of Supplementary materials as pozzolanes
– Material saving technique as hollow core deck
– Reinforcement with high content of recycled material and produced by renewable energy.

General differences are:
– More impact in module A2 for prefabricated concrete depending on longer processing of the product;
– More impact in module A3 for prefabricated concrete depending on fewer production sites;
– More impact in module A5 for Ready-mixed concrete depending on more activity's at building site.

Options for low impact:
– Prefabricated concrete moulded at indoor temperature even in winter and extra cement for increase temperature by the cement reactions is not necessary;
– Prefabricated elements could theoretical been moulded earlier in the projects to avoid hurry. More pozzolanes could been used if slow production is acceptable;
– Prefabricated concrete elements could be theoretically reused.

2.7.2 Life Cycle Cost assessment, LCC

Life cycle cost data are taken from the ongoing EU project SESBE [67]. Costs for the assembly are not calculated. Calculations follow the standard ISO 15685-5:2008 [40] and SETAC environmental code of practice [41].

Discount rate
The discount rate is set to 3 % and in sensitive analyses the discount rate are 2 % and 4 %.

Costs
In the table below, cost examples of materials, installation and energy are summarized. Costs are reported both in SEK and EUR (SEK =0.10082 EUR).

Cement (Basement)	1250	SEK/ton	126,03	EUR/ton
Aggregates	120	SEK /ton	12,10	EUR/ton
superplasticizer	25000	SEK /ton	2520,50	EUR/ton
Fly ash	5	SEK /ton	0,50	EUR/ton
EPS, 200 +40 mm BK	175	SEK /m^2	17,64	EUR/m^2
Mineral wool, 240 mm BK	111	SEK /m^2	11,19	EUR/m^2
Steel reinforcement	8,4	SEK /kg	0,85	EUR/kg
Installation of external wall elements (prefabricated)	142,33	SEK /m^2	14,35	EUR/m^2
Energy				
Electricity	0,55	SEK /kWh (July-Dec 2015)	0,06	EUR/kWh
District heat	0,842	SEK /kWh (average 2015)	0,08	EUR/kWh

Table 26: Materials, installation and energy costs

2.8 Cataloguing of recycling technologies and plants for different CDW

C&D waste is a mixture of different components such as concrete, wood, bricks, glass, metals and asphalt [51]. Most often, C&D materials are accepted as mixed recyclables due to the large amount of time it would require to sort them, except in some countries where there are strict regulation that require waste separation to minimize waste disposal and maximise reuse, upcycling and recycling (e.g. Germany). C&D recycling requires very heavy duty recycling systems because of the weight and size of the chunks of material. There is equipment for C&D recycling that utilizes a number of different devices to separate these materials by type. Typical processing steps include two- stage crushing, screening, sieving and removal of impurities and materials such as plastics, iron and steel.
Once separated, these commodities are bundled and sent to paying markets for recycling, rather than being sent to a landfill.

2.8.1 Sorting

Sorting of waste materials is a crucial step in recycling and it depends on the method of demolition. Waste materials need to be clean in order to be suitable for inclusion in the production of (building) products. Separating a larger number of different materials on-site, the amount of rubble and mixed materials will theoretically decrease, as shown in Figure 51. The sorting plant should be located either: at the landfill for inert waste or, at the landfill for non-hazardous waste, at a disused industrial building close to the inert or non-hazardous landfill, and at the location of the MBT or MRF (mechanical biological treatment plant). Separation close to the source will prevent the waste being mixed with other wastes, and increases the amount of materials suitable for recycling. For example, in Mulders' study [52] is reported that the following materials are preferred to be separated on-site: scrap, ferrous and nonferrous metals, cables, gypsum, AAC, rubble, wood A, B, and C quality, glass, and bitumen roof material. If these materials end up in the mixed waste stream or in an intended mono-stream, some of them will be difficult to filter out in off-site sorting.

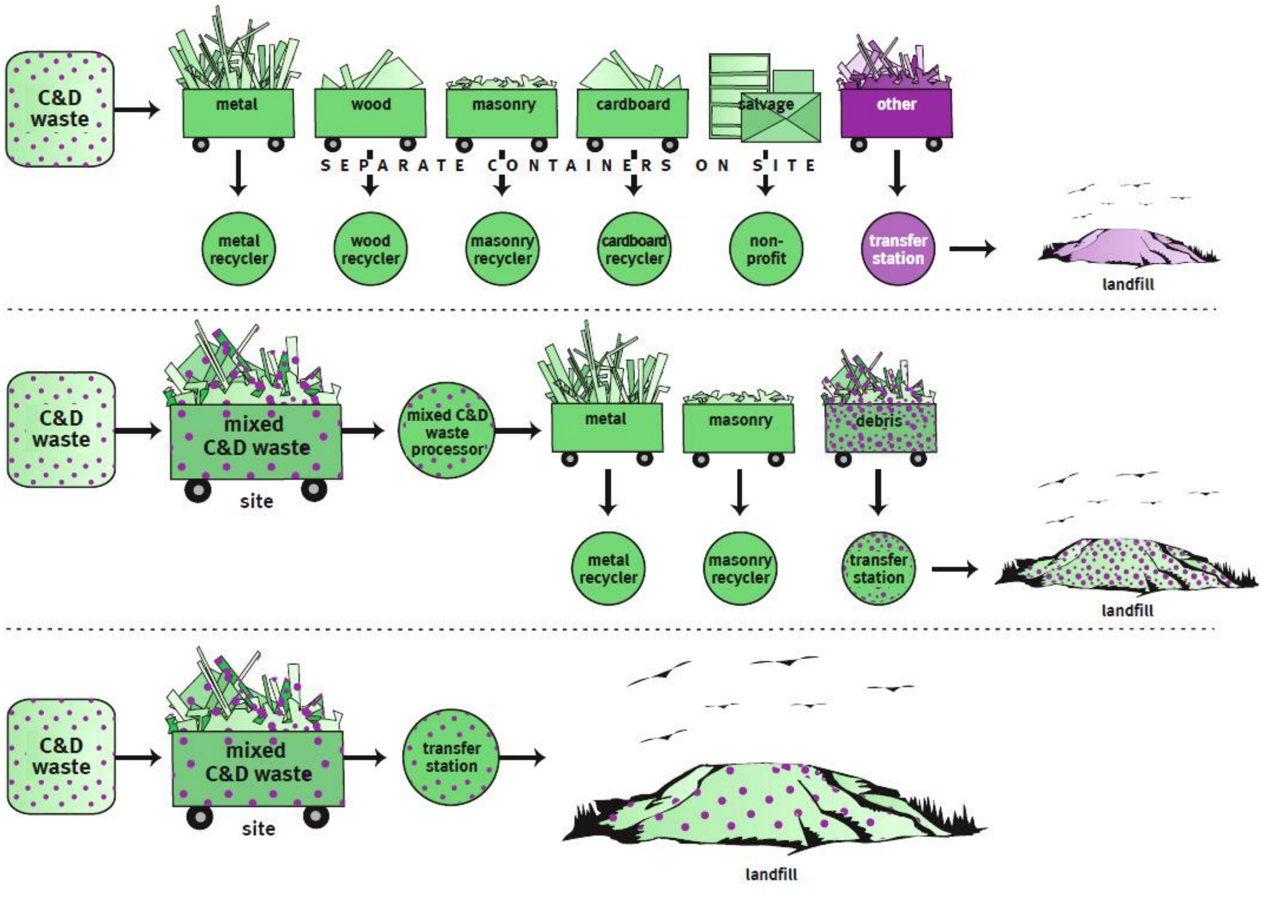


Figure 51: Sorting of materials at different stages leads to different amounts of material [53]

Once mixed materials are not separable anymore, the quality of the secondary material stream is lower, which complicates recycling at a high quality. The size of sorted residue of the sorting facility may increase due to improper sorting on-site. This residue is likely to be incinerated, and is therefore not available anymore for recycling. Furthermore, separation of the demolition waste is easier in case a building is designed to be taken apart at the end of its life. Therefore, in the design phase of the building deconstruction should be considered [54].

2.8.2 Reuse

Whenever possible (depending on material type and status of degradation), reuse is preferred over material recycling, because it is less expensive and quick. In this section, reuse options for mineral-based materials, wood and metals are discussed.

Ceramic clay bricks
Bricks can be re-used in their original purpose, use in the masonry of a construction. In order to prepare the brick for re-use, a temperature treatment can be practiced with the aim to remove mortar from brick surface: treatment of bricks at a high temperature leads to strains built up in the brick and mortar; this causes shear stress on the mortar, since the mortar is on the interface of the brick. As a result, crack formation on the interface sets the brick free. The recovered bricks are of the same quality as before heating. Alternatively, the mortar can be manually removed from the brick. Van Dijk [55] shows that cement dominated mortar requires a temperature of 540 °C for separation of the mortar and the brick. Higher temperatures are required for separating brick and mortar containing lime.
A higher temperature results in more cracks in the bricks. This will especially be the case if the masonry debris is presented in large lumps. The critical quartz solid phase transition temperature of the ceramic clay brick is 573 °C. In case a higher temperature is required for mortar separation the chance of fractures in the bricks increases. In order to lower the cracking percentage, the bricks can be separated mechanically before heating.

Wooden construction material
Depending on their connection means, wooden material, e.g. beams, floor boards, window frames and other wooden materials, can be reused in the same form as they are recovered, in case they are not containing any wood preservative. In order to increase reuse of wood, adjustments in the design and building phase can simplify full recovery of the material. Next to that, careful and selective dismantling is required in order to maintain the specifications of the wood.
Window frames and doors can be reused in their original purpose, however more stringent thermal requirements should be reflected and might require an energetic refurbishment.

Steel construction products
Re-use of steel can be in the form of products, like steel beams or steel portal frames, but also on the complete building level. For construction products, it is important to gain information on the properties of the material and the users' history.

2.8.3 Recycling within the building sector

After reuse of building materials, upcycling, recycling of the material within the building sector is preferred. The embodied energy of recycled products is, in general, lower than products made from virgin material. The use of recycled materials in construction will decrease the embodied energy of the building [52]. Currently, recycling technologies can be divided into three levels [56]:

- Level 1: Includes a mobile crusher with some classification screens. This technology is quite simple, often located at a demolition site and recycled materials for reconstruction at that site. Only ferrous impurities are separated through magnetic separation.

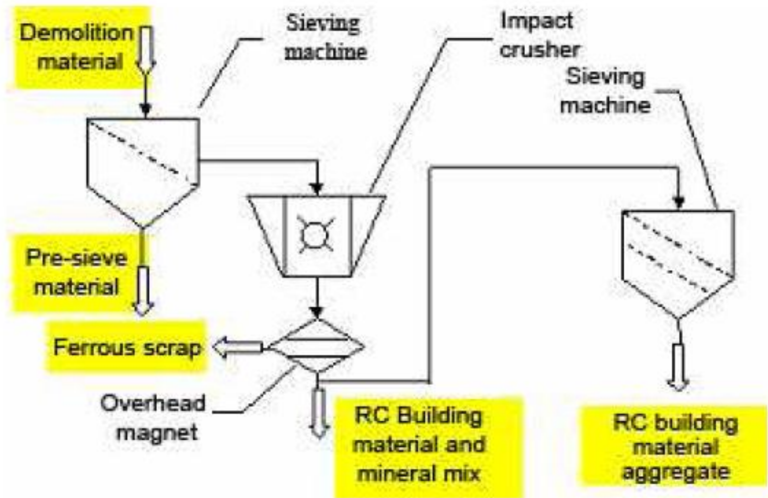


Figure 52: Mobile Plant scheme [57]

- Level 2: Includes equipment of level 1 with adding a metal separation and classification system based on different sizes. This technology may be installed at fixity or mobile with bigger capacity.

- Level 3: The complete technology including equipment of level 2 and adding a separation to remove the large pieces of wood, foam, plastic, nylon, etc. This separation can be by hand or mechanical removal. Small impurities can be removed by dry or wet screening, washing with high pressure water, pressing sludge, etc. This technology is used for recycled plants with medium and large capacity or put on the closed landfills.

Metal, wood, plastic, etc. are processed in different ways to be used as recycled materials (par. 2.8.4).
Therefore, there are three types of recycling plants:
– Mobile plant,
– Semi-mobile plant

– Stationary plant.

Mobile plants have the advantage to process the necessary throughput for economic feasible operation conditions on various locations. In the mobile plant, the materials is crushed and screened and ferrous impurities are separated through magnetic separation (Figure 52). The plant is transported to the demolition site itself and is suited to process only non-contaminated concrete or masonry waste. Mobile crushers are available on wheels and on tracks. Mobile crushers on wheels have to be equipped for public traffic. They can be transported as a semi-trailer on public roads, under consideration of permitted weight limits. Mobile crushers on wheels are cheaper and less heavy but higher than comparable mobile crushers on tracks. Mobile crushers on tracks can be moved on-site to have it as close as possible to the input material, which is not possible with the mobile crusher on wheels. Because of their heavy weight transports for both types of mobile crusher need special permissions from the transport authority.
In the semi mobile plant, removal of contaminants is carried out by hand and the end product is also screened. Magnetic separation for removal of ferrous material is carried out. End production quality is better than that of a mobile plant.
Stationary plants are equipped for carrying out crushing, screening as well as purification to separate the contaminants. Issues necessary to be considered for construction of the stationary plant are: Plant location, road infrastructure, availability of land space, etc. Stationary crushers do not have a chassis frame, so they have a lower feeding height than mobile crushers. Moreover, they can be supplied with electric energy, which produces less emission on-site. It also should be investigated in every particular case whether it is economically feasible with regards to energy price and costs for infrastructure. On stationary plants, the process steps and health & safety aspects can be optimized better than in mobile plants.
Different types of crushers are used in recycling plant namely jaw-crusher, impact crusher, impeller-impact crusher.

Jaw-crusher
Jaw crushers compact the feed material between moving plates. This type of crusher is advantageous for very hard material (e.g. granite) or as first step to crush larger blocks of medium hard material (e.g. Maltese hard stone, concrete, and reinforced concrete). Grain size of the output can be controlled by the gap size of the impact plates. Jaw crushers have the lowest abrasion costs related to the material throughput [58], but a disadvantageous grain form of the output material. Jaw crushers produce a variety of final grain sizes that have to be screened afterwards to get aggregates with the requested grain size distribution. Jaw crushers cannot be used for/ with asphalt and gravel.

Impact crusher
Impact crushers reduce the material size by shooting it with a rotating cylinder (which is equipped with steel bars) onto the covering cylindrical wall. Size reduction is done by virtue of impact. All kinds of material (incl. reinforced concrete) can be processed, except very hard stone (e.g. granite). Feed material size is determined by the size of the hopper. Grain size of the output can

be controlled by the gap size of the impact bars. Impact crusher produces the same variety of materials than jaw crusher, and it is suitable for all kind of materials.

Cone crusher
Cone crushers reduce the material size by means of grinding. Feed material size has to be below 160 mm, the final grain size is sand 0/12 mm to 0/60 mm. Cone crushers produce sand, screening is necessary only for special purposes. Cone crushers may only be used for small size input material (e.g. pre-crushed softstone).



Jaw crucher Impact crusher Cone crusher

Figure 53: Crusher plans

2.8.4 C&D waste typology

The bulk of the mass of C&D waste is mineral based material. In buildings different kinds of mineral-based materials such as concrete, stones, bricks, gravel, sand-lime brick, burned clay (roof tiles), bitumen, gypsum based materials, wood and rubble are installed. In demolition, a large part of the mineral-based material consists of mixed content that is currently crushed to a particular size, depending on the demand, before it is used in a next process.

Bricks and masonry
Bricks and masonry are generally assembled with cement, mortar or lime. Masonry can be recycled with or without mortar separation. If the brick and mortar are not separated, the masonry is crushed to a fine grain size smaller than 0.5 mm. The aggregates are mixed with clay and fired in a kiln in order to make clay bricks. Bricks and masonry waste could also be used in the construction of road base and drayage layer, and mechanical soil stabilizers due to its inertness after crushing and separation.
It is preferred to separate the clay bricks from the mortar in the masonry rubble, since the cement fraction will affect the strength of the brick when it is included in production of new bricks. By thermal treatment, the masonry is separated in cement and sand [59]. For different types of bricks, the added brick aggregates in production should be analyzed on strength and quality.
In Spain, masonry aggregates are used as a substitute for virgin aggregates for different types of stones [60]. In order to separate the masonry with contamination, all small particles were eliminated from the waste stream. The material stream remaining is crushed to the desired size while impurities are removed by the most common used method in Spain, the dry method: large size impurities are manually removed in an early phase of crushing.

The technology to include sand-lime bricks aggregates in the production of new sand-lime bricks is available. Production of sand-lime bricks runs as follows. Sand, lime and water is mixed in a reactor, in which the lime and the water react to a substance that sticks together [52]. This substance is pressed together and is placed in an autoclave, i.e. a pressure vessel, in which the temperature rises to 200 °C. The chemical reaction between the lime and sand that occurs in the autoclave, leads to hardening of the material to a sand-lime brick.
Aggregates from stony material can be used for production of sand-lime bricks as replacement for virgin sand. The production of sand-lime brick can remain the same when including recycled aggregates in the product. The preference is, however, to include sand-lime brick aggregates or concrete aggregates, not masonry, since masonry will lead to a notable color difference of the product.

Ceramic and tiles

Ceramics constructions products are used mainly for buildings. After a building is demolished, ceramic construction products can be crushed and then used as secondary raw materials for different applications, including road construction (sub-layer), cement clinker production, agriculture, embankments, tennis courts, substrate for green roofs and concrete aggregates. Crushed ceramic masonry units coming from the demolition of the building can also be used to replace primary raw materials in the manufacturing of an equivalent ceramic masonry unit.
Tile materials recycling are almost identical to bricks. Tile is often mixed with brick in final recycled product.
Roof tiles have a long life span and require little or no maintenance. After the end-of-life stage of a building, roof tiles can be removed, transported to a storage site and then reused in a new building.

Concrete

Concrete appears in two forms in the waste: non-structural concrete and reinforced concrete. Concrete constitute more than 40% of waste generated. Recycling of this waste by converting it to aggregate offers dual benefits of saving landfill space and reduction in extraction of natural raw material for new construction.
Concrete from construction, renovation and demolition (CRD) of old buildings can be recycled. However, there is difficulty in separating the stone, known as aggregate, from the cement for reuse in new structural concrete components. The cement-coated old concrete may weaken the new concrete if it is not treated properly.
Recycling of concrete is normally done in a recycling plant. The material is crushed and screened to produce all required grain sizes. Crushed concrete is recyclable as an aggregate of new concrete, and mostly replaces natural aggregate in earth construction like roads, etc. Crushing of concrete is noisy and dusty work, so concrete should first be transported to a suitable crushing plant.
Sand can be used as filler in trencher, as sub-layer under tiles, as sand for mortar and grout, for landscaping purposes and as aggregate for production of reconstituted stone. Mineral aggregates in various sizes and qualities from recycled concrete and also soft stone can be used to substitute virgin hard stone aggregates, which has to be seen as limited and high-quality resource.

Concrete aggregates from CDW can be used as general bulk fill, sub base material in road construction, canal lining, playground, fills in drainage projects and for making new concrete to a less extent.

Concrete aggregates from CDW can be used for substituting natural aggregates in concrete production. Use of up to 20% concrete aggregates from CDW as substitute of natural aggregates has a low influence on concrete properties and workability.

Concrete with or without recycled content should comply to EN 206-1 and EN 8005. Aggregates that are included in the concrete, for example, sand, gravel or concrete aggregates from CDW, need to comply with the EN 12620. Use of more than 50% of concrete aggregates for concrete production, requires adjusted calculation methods for the use of the concrete.

There are several technologies to prepare concrete for recycling. The following 4 technologies will be discussed: Crushing, sifting and washing; Advanced Dry Recovery (ADR); thermal treatment and smart crushing.

Crushing, sifting, with or without washing

This technology consists of the processes crushing, sifting and cleaning of the material. In the first step, crushing, the range of size of the material is chosen. After crushing, ferrous metals and lightweight materials are removed from the material stream by a magnet and a wind sifter, respectively, as to not contaminate the material stream. A small amount of these contaminants remaining in the material stream, indeed, can degrade the strength and durability of concrete produced with these recycled aggregates.

The remaining aggregates are sifted into two size categories, 0 to 4 mm and 4 to 16 mm or 4 to 32 mm depending on the demand. To eliminate possible remaining contamination, the aggregates are washed. Several washing techniques are available, ranging from rather simple to complex systems. The remaining materials are clean aggregates that can be used in concrete production, and sludge, which needs to be landfilled. In Figure 54 the crushing, sifting, washing method is depicted in a diagram.

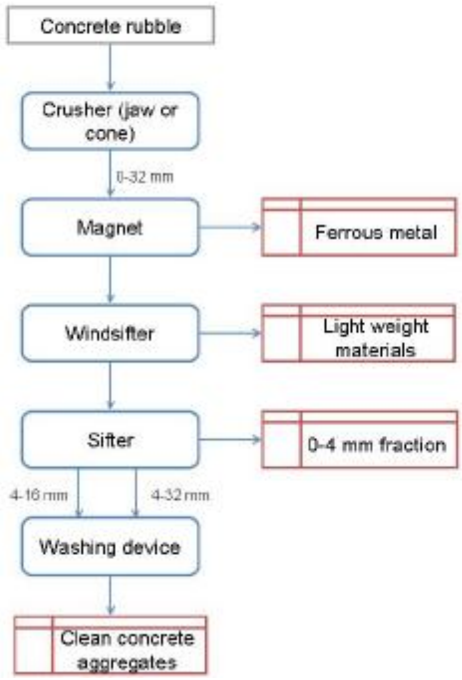


Figure 54: Crushing, sifting, washing method for preparing concrete *aggregates for recycling*

Advanced Dry Recovery

For the ADR technology, the focus is on reducing the amount of fines within the waste material. It is expected that for larger grain-sizes, contamination of ferrous metal is easily removable by magnets, while eddy current separators are able to separate non-ferrous metals. Therefore, the ADR starts when receiving 0 to 12 mm grain-sized particles. The crushed aggregates, sizes 0 to 12 mm, are separated in the machine in size 0 to 2 mm, the fine fraction, and 2 to 12 mm, the coarse fraction. Materials that are considered as contamination are in general lightweight and therefore directed to the fine fraction. In the ADR unit, kinetic energy is used to break the water bond that is associated with the fine particles. Thereafter, the separation of the fine and course fraction is executed on the aggregates density and size. In general, the fine fraction hosts 50% of the initial volume of the demolition concrete. Whether the cement in the fine fraction of the crushed material can be used in the production of cement requires additional research. The coarse fraction can be used as concrete aggregates.

Thermal treatment of concrete rubble

In order to completely close the concrete cycle, gravel, sand and dehydrated cement can be retrieved from concrete rubble. Figure 55 shows the process for thermal separation of concrete. First, the concrete rubble is crushed into small pieces with a jaw crusher. After crushing, the material passes a magnet, which extracts the steel from the material stream. Next is a rotary kiln, in which the temperature rises to 700 °C, which thermally separates sand and gravel from other materials.

Then, by a vibrating screen, coarse aggregate is separated from the material stream. By an air separator the fine aggregates are captured, leaving the cement stone at the end of the process. Whether the cement stone can be added in the production of Portland cement it should be tested more thoroughly.

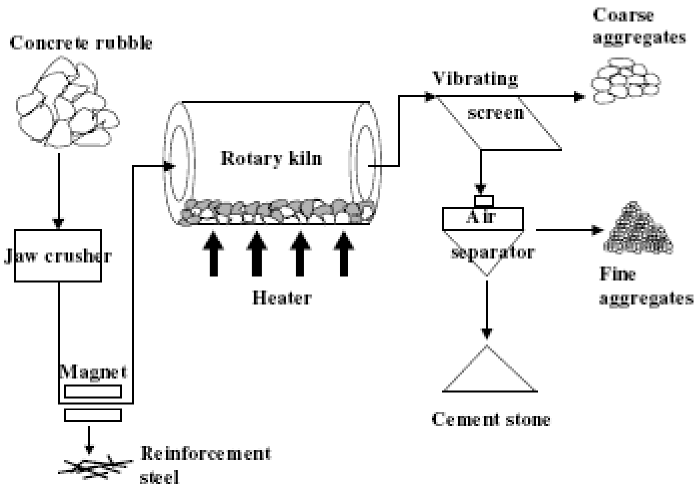


Figure 55: Preparing concrete rubble for recycling by thermal treatment (Source: [61])

Smart Crusher

Another new technology that is currently being developed is smart crushing, which aims at separating the concrete in it source materials, i.e. sand, gravel and cement with doing minor damage to the grains, depending on their strengths. Concrete, effectively, consists of different components, which have different strengths: coarse aggregate are usually the strongest part and the cement the weakest. In order to exert the right force on the aggregates, crushing and grinding are combined. The fine particles, i.e. cement, require thermal treatment to dehydrate the material in order to be used in the production of new cement.

Gypsum based material

Even though gypsum comprises a small share of the stony C&D waste material, it is 100% and extremely recyclable thanks to its chemical composition. There are two possibilities to use recycled gypsum-based waste materials:

- Closed loop recycling into new gypsum products. Closed loop recycling should be the end goal of the recycling industry in order to save primary raw materials, and minimize the usefulness of virgin materials, and minimize landfilling;
- Open loop recycling: using the recycling gypsum as a material in other products and applications. For example as a soil amendment for agricultural purposes, or as a retarder of cement.

The recycling process of gypsum materials is based on separation on-site and burning. The residue of the heated material is gypsum powder, which can be used in the production of gypsum material [62].

Metals

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 European List of Waste (LoW) is containing the following categories: ferrous metal and steel, copper, bronze and brass, aluminium, lead, zinc, tin, mixed metals, contaminated metals and cables.

Metals from construction have traditionally been recycled, since they are recovered in large quantities. Metal waste generated during demolition has the form of pipes, light sheet metal used in ventilation system, wires and sanitary fitting and as reinforcement in the concrete. Metals are recovered and recycled by re-melting. There are two modern ways of reprocessing steel: electric arc furnace (EAF) and basic oxygen furnace (BOF). In the EAF process 100% scrap is accepted. In the BOF process 25-30% of the ingredients are scrap steel, the rest is iron ore [63].

Steel can be recycled repeatedly without any degradation in terms of properties or performance in quality. Even if the steel is mixed with other materials, it can be magnetically separated for recycling. Most of the steel scrap from building demolition can be used in blast or electric furnaces for new material production. This new material is functionally equivalent to the original. However, melting, rolling and forming of recycled steel products consume considerable amounts of energy and resources, and create waste and emissions. Scrap metal has to be collected and transported over relatively long distances to the steel mills. Re-use of building component is an alternative end-of-life scenario where most of the heavy industrial processes can simply be bypassed.

Wood

Wood recovered in good condition in form of beams, window frames, doors, partitions and other fittings can potentially be reused, in case no wood preserver has been applied. Wooden material can, next to or after being reused, recycled. Reuse is, therefore, the only option for full recovery of the structural timber potential, and deconstruction should be the clear choice over demolition. The wood can then be recycled into another high quality wood product. If, for instance, the wood starts as a beam, after its useful life as a beam it can be either reused or recycled into a floor board. After its life as a floor board it can be made into a window frame. Each extra step, extra life form of the wood before incineration, is enlarging its useful lifetime.

Separating the wood on-site will increase the amount of high quality material that can be reused. Wood from a demolition site needs to be treated before it can be recycled, just because wood used in construction is often treated with chemicals to prevent termite infestation and warrants special care during disposal.

Next to that, wood can be recycled into chipboard. The wooden material is shred into small wooden chips, which can be used for making chipboard. Products that are made from this material do not have the same structural capacity and are therefore not usable for construction beams, floor etc. Chipboard can be used for making furniture. If furniture is considered to be part of the building sector, recycling wood into chipboard can be seen as recycling within the building sector.

CDW materials	Recycling technology	Recycled product
Brick and masonry	Burn to ash Crush into aggregate Heat to 900°C to ash	Slime burnt ash Filling material Hardcore Recycled aggregates for new bricks and foundations Thermal insulating concrete Traditional clay brick Sodium silicate brick
Ceramics and tiles	Crush into aggregate	Sub-layer in road construction Recycled aggregate Ceramic masonry unit replacement
Concrete	Crush into aggregate Advanced Cry Recovery Thermal treatment of concrete rubble	Recycled aggregate Cement replacement Protection of levee Backfilling Filler
Gypsum based material	Heat to retrieve gypsum powder	New gypsum products
Metals	Melt	Recycled metal Construction part in new building
Timber and Wood	Cut into aggregate Blast furnace Gasification od pyrolysis Chipping Molding by pressurizing timber chip under steam and water	Whole timber Chipboard for furnishing Furniture and kitchen utensils Lightweight recycled woodships Source of energy Wood-based panel Plastic lumber Geofibre Insulation board

Table 27: C&D Waste typologies, recycling technologies and recycled products

2.8.5 Innovative projects on CDW recycling technologies

Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste C2CA (FP7-ENVIRONMENT)

The development of mobile ADR equipment will be one of the important outcomes to be achieved during the first 18-months of project implementation. In combination with a mobile concrete

crusher it allows the on-site treatment of a large amount of materials and a significant reduction in road transport. C2CA case study [64] suggests that the usage of sensors to assess and remove coarse contaminants (wood, plastics, etc.) from the broken concrete at an early stage (just after the crusher) is a critical part of future recycling technologies. LCC analysis has shown that the development of mobile ADR technology makes recycling concrete into clean aggregate more profitable than on-site breaking for road base aggregate. Moreover ADR technology has shown to be cheaper than the wet process in producing high-quality aggregates. The use of ADR fines as raw material has been investigated, to produce “Green Clinker”.
C2CA project, also, proves that mechanical properties of concrete made of recycled aggregates depend on the amount of cement paste attached to the surface of the aggregates; so it has been shown that among various liberation routes, autogenous (attrition) milling, offers low complexity (mobile) and low-cost technology to remove the fragile mortar from the surface of aggregates. After milling, ADR efficiently separates the moist material into fine and coarse fraction.

From gypsum to Gypsum (Life)

The GtoG project has put in place an integrated approach to C&D waste by holistic management, starting from the major refurbishment/demolition sites to the reincorporation of the recycled gypsum in the manufacturing process via the processing of gypsum waste as a secondary raw material.
The project has developed all its technical activities through three actions:
1) Action A analysed and evaluated the current practices in deconstruction/demolition, C&D waste characterization, processing the gypsum waste for the production of recycled gypsum and its reincorporation into the manufacturing process.

2) Action B the project implementation actions, where five pilot projects implementing the deconstruction techniques, the decontamination and the waste qualification, reprocessing and reincorporation in gypsum manufacturing plants have been carried out in Belgium, France (2), Germany and UK. This action has been developed through the following sub-actions [65]:

– The 5 deconstruction projects. This activity has been implemented by the five demolishers in the project, who selected commercial buildings, where gypsum products and systems have been audited and deconstructed, using various techniques and practices. In all cases gypsum waste was dismantled manually or mechanically, segregated at source and transported to different recycling facilities according to the respective project's locations, for a posteriori processing into recycled gypsum. The pilot projects were all tertiary buildings located in countries where deconstruction is a usual practice.
– The 5 recycling projects. In this sub-action, the plasterboard wastes supplied by the deconstruction project have been processed and then transferred as recycled gypsum powder to the five manufacturer's plants to be reincorporated in the production process.

– The 5 reincorporation projects. Within the sub-action, the recycled powder supplied by the recyclers has been re-incorporated into the production process. The recycled gypsum powder used during the reincorporation phase has also been tested by a laboratory.

3) Action C, which monitored the impact of the project actions. The end results have been a report [66] on best practice indicators, the assessment of the carbon footprint of gypsum: landfilling versus landfilling route and the roadmap for implementing a gypsum sustainable value chain, where an outline plan has been determined in order to achieve a more widespread implementation of gypsum C&D waste recycling. The report presents a set of 37 Key Performance Indicators (KPIs) and the selected 29 Best Practice Indicators (BPIs) recognizing and encouraging the implementation of best practices. These BPIs address the entire gypsum value chain (deconstruction, recycling and reincorporation), being classified per category: technical, social, economic and environmental; and per stage: pre-deconstruction audit, gypsum-based systems deconstruction, gypsum waste traceability, end route, reception by the gypsum recycler, storage, processing and transport of the recycled gypsum, reception by the plasterboard manufacturer, storage, reincorporation, preprocessing and plasterboard manufacturing. The defined analytical framework can be used as a decision-making tool helping to increase the effectiveness of the gypsum End of Life recycling route, measuring the performance and progress of gypsum waste management, detecting the possibilities of improvement as well as monitoring changes over time.

Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste HISER (Horizon 2020)

The main objective in HISER is to develop and demonstrate novel cost-effective holistic solutions (technological and non-technological) for a higher recovery of raw materials from ever more complex construction and demolition waste (CDW) by considering circular economy approaches throughout the building value chain (from End-of-Life Buildings to new Buildings).

The following solutions have been proposed:

– Harmonized procedures, supplemented by an intelligent tool and systems for traceability of the supply chain, for highly-efficient sorting at source in demolition and refurbishment works.
– Advanced sorting and recycling technologies with automated quality control for the production of high purity raw materials from complex CDW.
– Development of optimized construction products (such as low embodied energy cements, green concretes, bricks, gypsum plasters and gypsum plasterboards or extruded composites).

While working on the HISER project 5 main innovative automated sorting and recycling technologies will be introduced to the market. All of them are aiming to achieve a better cost-effective recovery of the pure materials contained in the C&DW stony fraction.

1. New generation of sensor based automated sorting technology.

The innovative system will be the fusion of two very different optical sensor systems into one single system aiming to save around 35% costs and energy when comparing to inline separate sensor based sorting solutions. A popular approach is to split the light information via a beam splitter into two sensor systems (VIS and NIR-sensors). The resultant weakening of light makes this method not very powerful. Here, new ways must be found to develop a very compact optical sensor system. In addition to the detection, separation represents another challenge, especially for CDW. The aim should be to produce two good fractions from a waste stream in one step plus a third fraction with unwanted material. Such three way sorting machines will make high demands on the design and the quality of the input current. It will also be adapted for selectively sorting of contaminated particles arising from industrial assets (non-residential buildings). The engineering innovation in the HISER project according to an automatic sensor-based sorting machine is to find a harmonious interplay of all construction components, taking into account economical and energy efficiency boundary conditions.

2. Modernized electro-fragmentation technology

The adaptation of existing technology to the selective release of materials included in the red (adhered gypsum or insulating materials) and grey fractions (adhered particles or fibres reinforcing the concrete) of CDW will be the innovative challenge in HISER project. This step is essential for the production of a monophasic fraction and has to be based on intergranular breakage (i.e. fragmentation along grain boundaries) in order to avoid damaging the materials allowing then its high-value recycling. The evolved mobile electro-fragmentation will also aim to minimize the fine-size production and to develop a low energy intensive process of fragmentation to limit economic and environmental impacts of the recycling treatment plant.

3. New low-cost classification technology (ADR system)

One of the main environmental challenges in the construction industry is the existing of a strong social force in order to decrease the bulk transport of the building materials in urban environments. Considering this fact, applying more in situ recycling technologies for Construction and Demolition Waste (CDW) could be the key. To achieve this goal, a new low-cost classification technology, called Advanced Dry Recovery (ADR) is being developed. ADR performs purely mechanically and in the moist state, i.e. without prior drying or wet screening. This choice reduces process complexity and avoids problems with dust or sludge. ADR is applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles. It uses kinetic energy to break the bonds that are formed by moisture and fine particles and can classify materials almost independent of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product and a fine fraction, which includes the cement paste and contaminants such as wood, plastics and foams. Within HISER, field experiments will be performed by means of a novel mobile pilot plant containing different unit operations such as: attrition milling, screening (>16mm), and mobile ADR insulation beside integration of the sensors and quality control elements. Both the up-scaling of the ADR technology and the process design for the integration of all unit operations in the plant (requiring basic design, detailed engineering and built engineering) will be carried out as to finally build the mobile pilot plant.

4. Innovative recycling technologies for gypsum plasterboards
HISER partners will innovate in the following gypsum recycling technology:
• Development of low cost mobile compact equipment – instead of multistage recycling processes, this compact portable apparatus will guarantee the selective onsite recovery of pre-consumer gypsum and cardboard with purity levels of 85% for both fractions.
• Development of advanced gypsum sorting and recycling schemes - providing high purity recycled gypsum, enabling manufacturers of gypsum building products to easily accept higher amounts of recovered gypsum from waste postconsumer products. NIR and X-ray fluorescence (XRF) sensors will be integrated in such novel schemes. This approach constitutes an innovative field of application for automated identification and sorting.

5. New recycling technologies for C&D waste wood and other minor emerging waste fractions
Develop and validate new cost efficient sorting and commuting technological solutions for C&D wood, glass and mineral wool waste materials is one of the aim of HISER project. It will integrate material pre-crushing, fine crushing, sorting and cleaning into one system, which effectively separates impurities and classifies the cleaned raw material into desired fractions. Refining and post refining processes will be optimized for the production of high quality wood fractions and fibers from both C&D wood waste and mineral wool waste to be used as reinforcement in composites and gypsum plasterboards. Additionally, specific refining and post refining processing techniques will be adjusted for producing high quality silica from C&D glass waste to be used as reactive filler in low-CO2 footprint cement.

3. CONCLUSIONS AND RECOMMENDATIONS

The commercial and scientific state of the art revealed that the use of prefabricated elements from CDW in Europe is still a relatively undeveloped topic and further research is required.

When it comes to statistical data with regard to the use of recycled content in prefabricated construction, no information from which the proportion of recycled materials can directly be derived for the production of prefabricated elements is available. This relates to the fact that CDW is still not used for prefabrication for structural elements. In order to promote the use of CDW in prefabricated construction set goals that could be followed up would be very important.

Moreover, as shown in the examples in section 2.2, in Europe there are many national regulations regarding the classification of recycled concrete aggregates. Each country seems to use its own abbreviation and typology. This is very confusing, as e.g. „Type 1“ aggregate in Germany according to DIN 4226-100 is the highest quality RC-aggregate, whereas „Type 1“ by RILEM standards is the lowest quality RC-aggregate.
Similarly, the terms RCA, RMA and MRA seems to have their own meaning in each country as well.

In order to endorse the use of RC-aggregates throughout Europe, a harmonised EU standard should be set for the classification of RC-aggregates.

Taking in consideration CDW based prefabricated concrete construction, although several developments and research initiatives are ongoing (although not published yet), no examples were available with regards to structural or façade elements. The only examples relate to precast concrete stones that, however, are not used for building construction purposes. It is understood that the main barrier lies within their production as hardening times for such elements are still too high due to an increased water demand. Further research in combination with the construction of prototypes is required.
Besides, from the analysis developed in this deliverable, while precast concrete elements may be material efficient, they are not yet suitable for reversible construction. Most of their joints and nodes rely heavily on grouting to obtain sufficient stiffness and bonding. While it might be possible to separate slabs again using a sawing device, wall-to-wall connections seem difficult to dismantle without destroying at least one of the elements.
A promising approach could be the use of tension rods (Figure 9) to reversibly connect the precast concrete elements. These connection types have the advantage of being ductile, which leads to increased seismic performance.

Considering CDW based prefabricated wood construction, in Europe timber as a renewable resource and construction material benefits from large forestland. Due to forestation and an increasing lumbering, current consumption rates requested by the construction and energy sector can still be satisfied. However, a long-term provision of the resource as a construction material in relation to the rapidly increasing demand by the industry is not likely, even though capacities will be further expanded. A revised strategy with cascade utilisation for a sustainable use of timber, where an early use of timber as energetic recovery should only be considered at the end of life of an element or the material, is therefore urgently required. A concept to reuse entire timber elements is described in section 2.5.2. This approach eliminates treatment procedures, but product liability issues make each reuse case a unique engineering decision, requiring great expertise, which the mass market might lack.
When it comes to recycled timber on the basis of CDW, the situation is quite challenging. According to a German wood insulation panel manufacturer, using crushed wood from CDW for insulation panel production poses additional difficulties in machine calibration due to fluctuating batch qualities and impurities. Even small amounts of mineral constituents may lead to production problems. Besides, they have access to pure wood chips as by products from local sawmills.
The crucial part of timber CDW recycling therefore lies within fast and efficient testing methods for contamination, sorting methods and common legal standards to achieve a homogenous product similar to the common mineral RC-aggregates. Although market prices of timber may be still too low for the reuse being economic, appropriate EU legislation could pave the way for future timber CDW reuse.

A brief LCA/LCC analysis has also been conducted in this deliverable, with the aim to underline advantages of prefabrication respect to conventional construction. More in details, as a preliminary reference building, an analysis based on concrete elements was carried out, because of the completeness of data on such subject. Environmental comparison between ready-mixed concrete vs. precast concrete show little fundamental differences between the methods. There are other factors within each production method that have more impact, e.g. mix design, type of cement used, supplementing with pozzolanes, material-efficient element profiles and use of recycled reinforcement produced with renewable energy.

Finally, an in-depth study and cataloguing of recycling technologies and plants of the different CDW, necessary to feed the function of the DSS related to possible end-uses, is reported. Different steps and strategies of recovery materials from CDW, the typologies of recycling plants, the available tecnologies and materials that can be recycled are in detail shown, in order to create a starting point for the realization of the BIM-compatible DSS for CDW estimation and management.

4. REFERENCES

[1] UEPG Annual Review 2015-2016 EUROPEAN AGGREGATES, ASSOCIATION - A Sustainable Industry for a Sustainable Europe, UEPG aisbl, Rue d'Arlon 21, 1050 Brussels, Belgium

[2] Bundesverband Baustoffe – Steine und Erden e.V.: Mineralische Bauabfälle – Monitoring 2012, Bericht zum Aufkommen und zum Verbleib mineralischer Bauabfälle, Berlin, 2015

[3] European Topic Centre on Sustainable Consumption and Production: EU as a Recycling Society-Present recycling levels of Municipal Waste and Construction & Demolition Waste in the EU, Prepared by: Christian Fischer and Mads Werge, European Topic Centre on Resource and Waste Management, April 2009, Project manager: Almut Reichel, European Environment Agency

[4] Mantau, U. et al. 2010: EUwood - Real potential for changes in growth and use of EU forests. Final report. Hamburg/Germany, June 2010

[5] Abstract Constribution: Waste Wood Situation in Europe and Germany Authors: Peter Meinlschmidt, Dirk Mauruschat, Robert Briesemeister, First published: 24 February 2016

[6] P. Concalves and J. de Brito. Recycled aggregate concrete (RAC)-comparative analysis of existing specifications. *Magazine of Concrete Research,* 62(5), pp. 339-346, 2010.

[7] R. K. Dhir. *In: Proceedings of the International UKIERI Concrete Congress*, New Delhi, India, 8-10 March, 2011, pp. 157-182.

[8] DIN 4266-100:2002. Aggregates for concrete and mortar-Recycled aggregates. Deutsches Institut Fur Normung, 2002.

[9] DAfStb Guideline: Concrete with recycled aggregates. German Committee for Reinforced Concrete (DAfStb), 1998.

[10] EN 206:2013+A1:2016. Concrete-Specification, performance, production and conformity. European Committee for Standardization, Brussels, 2016.

[11] LNEC E471. Guide for the use of recycled coarse aggregates in hydraulic binders. National Laboratory for Civil Engineering, Lisbon, Portugal, 2006.

[12] BS 8500-2:2015+A1:2016. Concrete-Complementary British Standard to BS EN 206. Part 2: Specification for constituent materials and concrete, British Standards Institution, London, 2016.

[13] CUR Report 5. Masonry rubble granulates as aggregate material for concrete. CUR, Gouda, 1994.

[14] ARMASUISSE Instruction technique (tV) 70085. Utilisation de matériaux de construction minéraux secondaires dans la construction d'abris. ARMASUISSE, Berne, 2006.

[15] COPRO PTV 406. Granulats de debris de demolition et de construction recycles. Impartial Certification Body in the Construction Sector (COPRO), Brussels, 2012.

[16] RILEM TC 121-DRG Specifications for concrete with recycled aggregates. Materials and Structures 27(173), pp. 557-559, 1994.

[17] Construction and Demolition Waste Management in Sweden, Version 2-September 2015. http://ec.europa.eu/environment/waste/studies/deliverables/CDW_Sweden_Factsheet_Final.pdf

[18] Construction and Demolition Waste Management in Finland, Version 3-December 2015. http://ec.europa.eu/environment/waste/studies/deliverables/CDW_Finland_Factsheet_Final.pdf

[19] Construction and Demolition Waste Management in Germany, Version 2-September 2015. http://ec.europa.eu/environment/waste/studies/deliverables/CDW_Germany_Factsheet_Final.pdf

[20] Construction and Demolition Waste Management in Germany, COWAM Project, 2006. http://cowam.tec-hh.net/Germany_CD_Waste.pdf

[21] Construction and Demolition Waste Management in Austria, Version 2-September 2015. http://ec.europa.eu/environment/waste/studies/deliverables/CDW_Austria_Factsheet_Final.pdf

[22] Jianzhuang Xiao, Deng Lu and Jingwei Ying: Durability of Recycled Aggregate Concrete: An Overview (Journal of Advanced Concrete Technology Vol 11, Dec 2013)

[23] http://www.feess.de/assets/RC_Beton/feess_flyer_os.pdf

[24] Fachbeitrag Aycil/Hlawatsch/Kropp, R16, 19. und 20. September 2016, Aycil, H.; Hlawatsch, F.; Kropp, J.: Hochwertige Verwertungsmöglichkeiten für Porenbetonrezyklate

[25] Forschungsvereinigung Kalk-Sand EV, Schlussbericht: Entwicklung eines Recycling-Mauersteins unter Verwendung von Abbruchmaterial und Baurestmassen und Anwendung der Kalksandstein-Technologie, Berichterstatter: Dipl.-Ing. Wolfgang Eden, Prof. Dr. rer. nat. Bernhard Middendorf, Frauenhofer IRB Verlag, 2009

[26] FDB Professional Association of German Precast Concrete Construction: Precast concrete elements in multistorey and industrial construction – Basic principles of planning, Verlag Bau+Technik GmbH Düsseldorf, 2009

[27] European Council Directive 96/53/EC of 25 July 1996

[28] http://www.vroom.nl/en/products/5-precast-foundation-beams

[29] http://www.vroom.nl/en/products/15-precast-concrete-piles

[30] Waste wood ordinance (2002) Ordinance for requirements in relation to the utilisation and disposal of wood waste, KrW-/AbfG 6.20.

[31] Meinlschmidt et al (2013), New ways of sorting and recycling of waste wood, In: *Proceedings of the Berlin Recycling and Raw Materials Conference 6, Neuruppin 2013,* TK PRESS, pp. 153-176.

[32] http://www.proholz.at/holz-ist-genial/co2-neutral/kohlenstoffspeicher/

[33] Kaufmann, H. Nerdinger, W. (2011), Constructing with Wood – ways into the future, [Exhibition catalogue held in Munich 10.11.2011 – 05.02.2012], ISBN 978-3-7913-6392-9, PRESTEL PRESS Munich, London, New York.

[34] Cheret, P., Schwaner, K., Seidel, A., (2014), Urban timber construction, handbook and planning guide, DOM Publisher Berlin

[35] Bojic, D. (2015): Application possibilities and application limits for ecological building materials for multi - storey buildings in the urban area: Development of a concept for an ecological component catalogue for buildings in building classes 4 and 5, Study Report

[36] ISO 14040:2006: Environmental management -- Life cycle assessment -- Principles and framework

[37] ISO 14044:2006: Environmental management -- Life cycle assessment -- Requirements and guidelines

[38] The International reference Life Cycle Data system (ILCD) handbook- JRC-IEA (2010)

[39] EN 15804:2012+A1:2013: Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products

[40] ISO 15686-5:2008: Buildings and constructed assets -- Service-life planning -- Part 5: Life-cycle costing

[41] Environmental life-cycle costing: a code of practice. SETAC (2011)

[42] Lisanne Mulders, High quality recycling of construction and demolition waste in the Netherlands, Master Thesis, 2013

[43] DDC. (2003). Construction & demolition waste manual. Prepared for NYC Department of Design & Construction by Gruzen Samton LLP with City Green Inc, New York.

[44] Edge Environment. (2011). Construction and demolition waste guide – Recycling and re-use across the supply chain. Prepared for the Australian Government, Department of Sustainability, Environment, Water, Population and Communities.

[45] ACI_555r-01 (2001), Removal and Reuse of Hardened Concrete. (Reported by ACI Committee 555): Pp 26.

[46] Hermalatha B.R, Nagendra Prasad, B.V. Venkata Subramanya, Construction and demolition waste recycling for sustainable growth and development, Journal of Environmental Research and Development, Vol.2 No.4, April-June 2008

[47] 1 Tam, V.W.Y., and C.M. Tam. (2006). A review on the viable technology for construction waste recycling. Resources, conservation and recycling 47(3): 209-221

[48] Del Río Merino, K., P.I. Gracia and I.S.W. Azevedo. (2010). Sustainable construction: Construction and demolition waste reconsidered. Waste management and research 28(2): 118-129

[49] Lisanne Mulders, High quality recycling of construction and demolition waste in the Netherlands, Master Thesis, 2013

[50] Damgaard, A., A.W. Larsen and T.H. Christensen. (2009). Recycling of metals: Accounting of greenhouse gases and global warming contributions. Waste management and research 27(8): 773-780.

[51] Commission Decision 2000/532/EC, http://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32000D0532

[52] Lisanne Mulders, High quality recycling of construction and demolition waste in the Netherlands, Master Thesis, 2013

[53] DDC. (2003). Construction & demolition waste manual. Prepared for NYC Department of Design & Construction by Gruzen Samton LLP with City Green Inc, New York.

[54] Edge Environment. (2011). Construction and demolition waste guide – Recycling and re-use across the supply chain. Prepared for the Australian Government, Department of Sustainability, Environment, Water, Population and Communities.

[55] Van Dijk, K. (2004). Closing the clay brick cycle. (doctoral thesis). ADVS b.v. ,Noordwijk

[56] ACI_555r-01 (2001), Removal and Reuse of Hardened Concrete. (Reported by ACI Committee 555): Pp 26.

[57] Hermalatha B.R, Nagendra Prasad, B.V. Venkata Subramanya, Construction and demolition waste recycling for sustainable growth and development, Journal of Environmental Research and Development, Vol.2 No.4, April-June 2008

[58] http://www.lareinainternationalschool.in/6519/hard-materials-jaw-crusher/

[59] Tam, V.W.Y., and C.M. Tam. (2006). A review on the viable technology for construction waste recycling. Resources, conservation and recycling 47(3): 209-221

[60] Del Río Merino, K., P.I. Gracia and I.S.W. Azevedo. (2010). Sustainable construction: Construction and demolition waste reconsidered. Waste management and research 28(2): 118-129

[61] Mulder, E., T.P.R. de Jong and L. Feenstra. (2007). Closed Cycle Construction: An integrated process for the separation and reuse of C&D waste. Waste management 27(10): 1408-1415

[62] BIO Intelligence Service, Service Contract on Management of Construction and Demolition Waste – SR1. Final Report Task 2, February 2011, Framework contract ENV.G.4/FRA/2008/0112

[63] Damgaard, A., A.W. Larsen and T.H. Christensen. (2009). Recycling of metals: Accounting of greenhouse gases and global warming contributions. Waste management and research 27(8): 773-780

[64] http://www.c2ca.eu/activities/the-c2ca-project/

[65] Universidad Politécnica de Madrid (UPM), REPORT ON BEST PRACTICE INDICATORS FOR DECONSTRUCTION, RECYCLING AND REINCORPORATION PRACTICES, Deliverable of Life project GTOG: From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry, June 2015

[66] Recovering SARL, EUROPEAN HANDBOOK ON BEST PRACTICES IN DECONSTRUCTION TECHNIQUES, Deliverable of Life project GTOG: From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry, March 2015

[67] SESBE Smart Elements for Sustainable Building Envelopes funded as a collaborative project by the European Commission within the 7th Framework Programme (FP7-2013-NMP-ENV-EeB)

DISCLAIMER