RE4 Project

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

D2.1 CDW specifications and material requirements for prefabricated structures	
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Acronyms

CBI	Swedish Cement and Concrete Research Institute AB
C&D	Construction and Demolition
CETMA	CEntro di progettazione, design & Tecnologie dei MAteriali
CDW	Construction and Demolition Waste
CW	Construction Waste
DoF	Degrees of Freedom
FTIR	Fourier transform Infrared
NIR	Near-InfraRed
QUB	Queen's University of Belfast
ROS	ROSWAG ARCHITEKTEN GESELLSCHAFT VON ARCHITEKTEN MBH
PSV	Polished Stone Value
SC	Shell Component
XRF	X-Ray Fluorescence
XRD	X-Ray Diffraction
WP	Work Package

1. Introduction

1.1. Task scope and objectives

The present document is included in the framework of the ongoing RE4 research project, funded by the European Commission in the context of Horizon 2020 research funding programme, call H2020-EEB-2016. It reports the activities done in Task 2.1, led by Stam with the collaboration of CDE Global Limited (CDE), Centro di Progettazione, Design & Tecnologie dei Materiali (CETMA), the Swedish Cement and Concrete Research Institute AB (CBI) and Queen's University of Belfast (QUB).

Task 2.1, *CDW material specifications,* is included into the context of Work Package (WP) 2 *Strategies for innovative sorting of CDW and reuse of structures from dismantled buildings*, which was forecasted to begin on Month 1 of the project (September 2016) and to end by Month 24 (August 2018) of the project. In particular, Task 2.1 timing foresaw the activities to be performed from Month 1 to Month 4 (December 2016).

The main goal of the task is to define a full set of features that are required for two of the main products of WP 2, namely the weight-based separating system (to be developed and prototyped in Task 2.3) and the robotic-aided sorting system (Task 2.4). Once the constraints are defined as well as features for the input and output materials, the preliminary technical requirements for the two systems will be defined within the relevant tasks.

In particular, the most interesting features to be defined during Task 2.1 activities are divided into chemical composition (percentages of different components, contamination level, etc.) and physical characteristics (size ranges, densities, typologies, etc.), at the different points of the process chain. For sake of clearness, this concept chain is represented in Figure 1.1, together with an indication of the different sections of the present document which deal with each single step and the features of the materials which are analysed.

1.2. Relevant work package input

The activities of Task 2.1 reported in the present document are strictly related to other tasks, since they represent the collection of requirements for tools and systems, which will be developed later in RE4 project. In order to define the materials requirements and features for the further development activities, the samples collection of CDW performed in Task 4.1 gave crucial technical information about materials to be separated and sorted, that were included in this report. Moreover, Task 4.2 *Characterisation of CDW-derived materials* gave an important technical input for the definition of system input and output from a material composition point of view. Referring to the main output and tasks that need information and results of this deliverable, they are mainly internal to the same Work Package. In fact, Task 2.3 will use the features and requirements defined in Sections 2.2, 3.1 and 4.3 for the development and fine tuning of weight-based CDW separating system, while Task 2.4 will base its algorithm, sensors and robotic layout on the information taken from Sections 3.1, 4.1, 4.2, 4.3 and 4.4. Their main outputs (Deliverable 2.3 *Weight and size-based CDW separation methods* and Deliverable 2.4 *Classification and sorting by using NIR sensors and robot*, respectively) will be developed according to the requirements and constraints written here.

1.3. Summary

During Task 2.1 activities, different levels of technical requirements for the input and output material of Work Package 2 separating and sorting systems were collected. This was done to fulfil the needs of further activities within the project, such as the material characterization and the development of prefabricated elements for building refurbishment and construction, starting from CDW-derived recycled materials, under the perspective of a circular economy, environmental friendly loop of construction, deconstruction, demolition, re-development and prefabrication of building parts.

The structure of the report was defined in order to linearly follow the distribution of activities among the task and its timeline.

In Section 2 the first steps of the material flow are described, starting from a characterization of European CDW to further detail the processing performed by CDE weight-based separating system, which will be developed during the Task 2.3 by CDE in collaboration with Stam, QUB, CBI and CETMA. In particular, Paragraph 2.1 takes a step back in the process chain, focusing on the unsorted materials to be taken as input by CDE's system, and their formal definition according to the samples collected during Task 4.1 activities. Afterwards, CDE's system features are explored in Sections 2.2, focusing on the results of the separation system, and analysing the range of size of its output elements and the foreseen error rate of the system.

Section 3 gives an overview of the features that are expected by Stam's sorting system (developed in Task 2.4) point of view, with main reference to the concept layout of the system itself and its consequent physical and functional constraints. The following Section 4 is then focused on the output requirements for Stam's robotic-based sorting system: Sections 4.1 and 4.2 define the requirements for output materials in order to fulfil the needs of WP 4 and 5 activities, respectively. Section 4.3 characterizes the materials to be sorted and their sizes, while 4.4 is focused on the system performance estimation in terms of error rate. The conclusions of this requirement collecting work are drawn in Section 5.

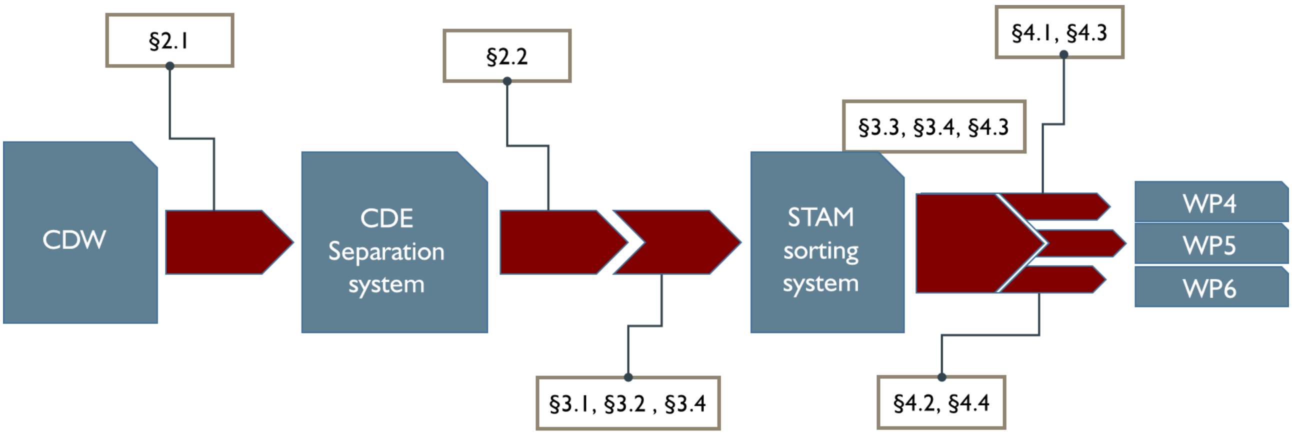


Figure 1.1: Sections of Deliverable 2.1 in which the different process steps are analysed

2. Technical requirements on input and output of CDE separating system

Building C&D is defined as the building or tearing-down of buildings and the needed structures. Both processes produce material wastes but the relevance of demolition is higher since on a per building basis, demolition waste quantities may be 20 to 30 times as much as construction debris. Demolition contrasts with deconstruction, which involves taking a building apart while carefully preserving valuable elements for re-use. Direct investigation of the C&D processes is not within the scope of the Project but will affect indirectly CDW to be separated and eventually sorted as the waste materials will present different features depending on the nature of demolishing process (punctual demolition vs explosive demolishment). Another fact that influences the C&D process and consequently the produced material is the building typology and geography. For the RE4 project, to make sure that samples for material characterization and system tests are relevant, 4 different building typologies were considered:

- Northern Europe residential buildings;
- Northern Europe non-residential buildings;
- Southern Europe residential buildings;
- Southern Europe non-residential buildings;

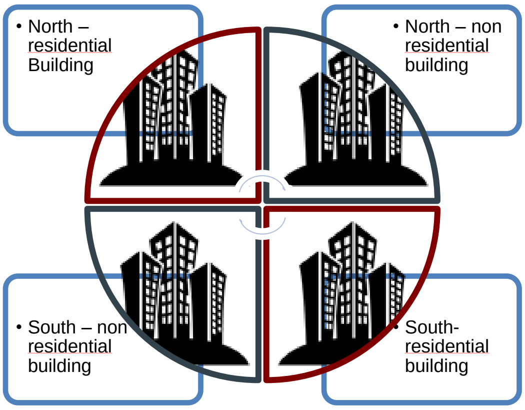


Figure 2.1: Building typologies in scope for the RE4 project

UK and Sweden/Norway were considered as reference states for northern Europe, while for southern Europe France was selected.

2.1. CDW: EU availability and composition

Construction and demolition waste (CDW) has its origin within different stages of the life cycle of buildings, including the execution and its partial or total demolition. Wastes generated at the end of life of a building will depend primarily on its typology (e.g. residential, industrial), construction procedures and materials used (e.g. concrete, wood, metals), deconstruction criteria and demolition techniques adopted (e.g. traditional, selective).

In recent decades, several studies have been conducted to estimate the amount and composition of CDW generated from different geographical areas and building typologies. CDW streams depend mainly on degree of industrialization and technologies applied in each region, the degree of structural and functional obsolescence of buildings and the regulations governing the conservation of buildings, construction techniques or waste reduction criteria adopted.

CDW accounts for approximately 25%-30% of all waste generated in the EU and consists of numerous materials including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil, many of which can be recycled [1]. The total volume of CDW for EU is estimated to be 970 million tons/year, representing an average value of almost 2.0 ton/per capita, with a wide geographical variation. Generation rates of CDW in EU countries vary between 0.2 and 5.5 tonnes, with most new EU member

1 http://ec.europa.eu/environment/waste/construction_demolition.htm

countries showing rates below 1 tonne and countries (e.g. United Kingdom and Germany) around 2 tonnes [2](Figure 2.2).

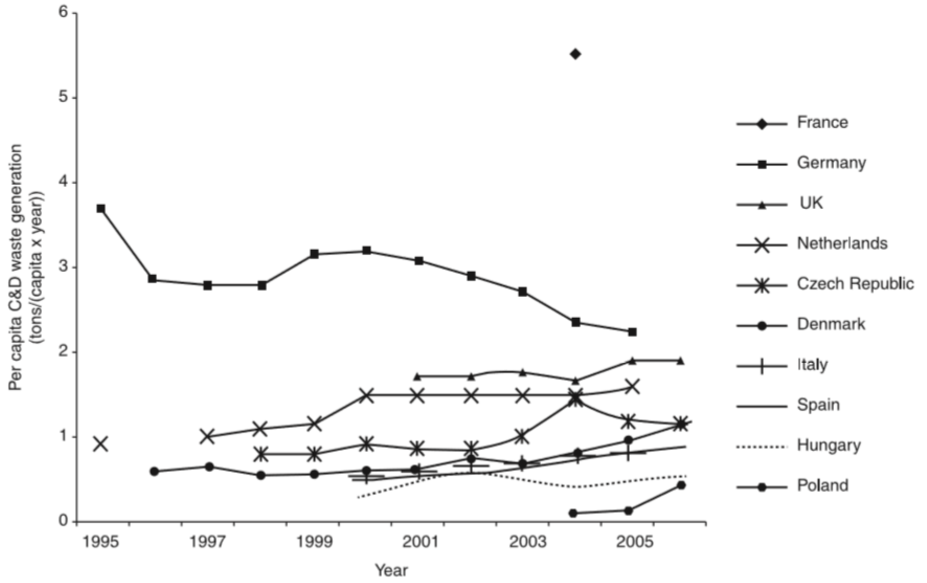


Figure 2.2: CDW generation in selected EU countries [3]

CDW waste recycling rates as well as their composition vary strongly between EU member countries (Figure 2.3).

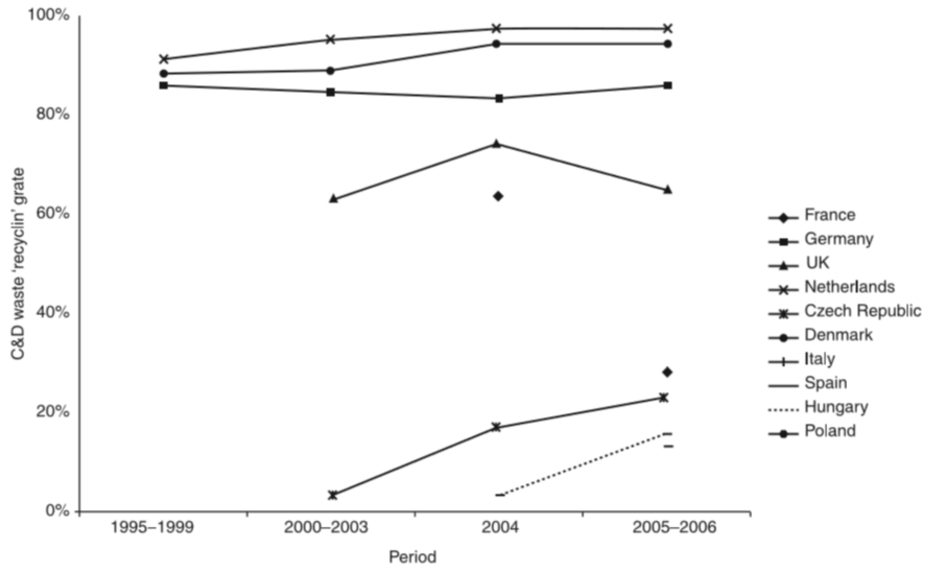


Figure 2.3: Recycling rates of CDW in selected EU countries [3].

[2] AA. VV., Handbook of concrete and demolition waste, Woodhead Publishing, 2013.
[3] Fischer C., Werge M, EU as a Recycling Society, Present Recycling Level of Municipal Waste and Construction and Demolition Waste in the EU, European Topic Centre on Sustainable Consumption and Production, 2009.

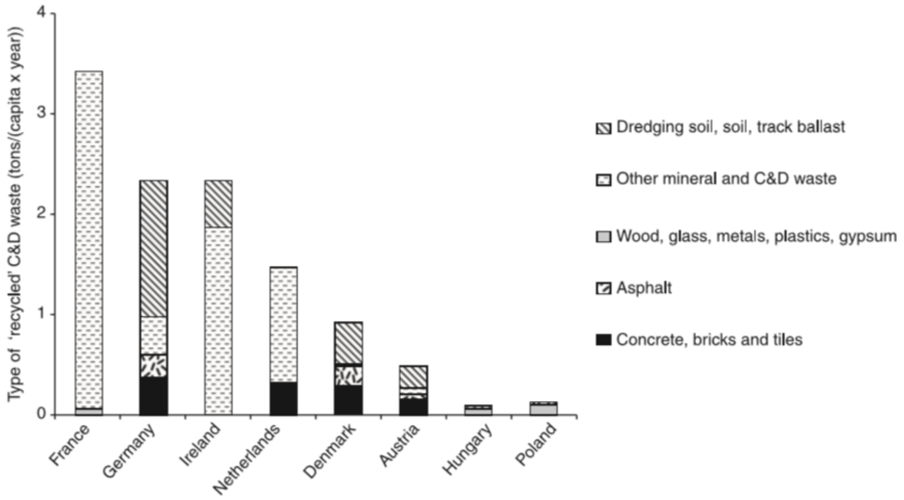


Figure 2.4: Composition of CDW in selected EU countries [3].

In terms of CDW composition, the majority is generally inert consisting in a mixture of components (e.g. concrete, bricks, glass, metals and wood) in which the degree of heterogeneity depends on the origin from demolition or construction works (Figure 2.4). CDW indeed arises from activities such as the construction, total or partial demolition of buildings and civil infrastructures. Construction waste (CW) is generated as a result of work executed on buildings from the foundations up, and by civil engineering works (e.g. roads, railways, canals, dams, sports and leisure facilities, ports and airports, etc.). The composition of CW depends on the type of construction work and the techniques used. It falls into five main categories: 1. soil (sand, clay, stones, mud, etc.), 2. packaging waste from building materials (wooden pallets, plastic, cardboard, etc.), 3. remains of building materials (of stony and non-stony nature); 4. hazardous waste (e.g. materials and substances that may include some dangerous features) and 5. others (i.e. organic materials). Demolition waste (DW) is a product of dismantling at the demolition stage or of the restoring/ repairing of buildings. The composition of DW depends on the construction techniques and materials used in the building to be demolished. It falls into four main categories: 1. non-stony waste (steel, iron, aluminium, copper, glass, wood, plastic, etc.), 2. stony waste (concrete, mortar, ceramics, aggregates and mixtures thereof), 3. hazardous waste (material containing asbestos, lead, zinc, paints etc.) and 4. others (i.e. organic materials). DW is usually more homogeneous than CW (absence of soil and packaging waste), it has a greater volume and weight. There is a greater likelihood of hazardous waste in demolition works than in construction (absence of past restrictive regulations on the use of certain hazardous materials) [2].

2.2. CDW processing by CDE Global

Within RE4 Project, CDE Global is responsible for processing materials and structures, resulting from buildings demolition, usable for research and demonstration activities. These materials are, specifically, allocated to WP4 (Technical characterization of CDW-derived materials for the production of building elements), WP5 (Development of precast components and elements from CDW) and WP6 (Pilot level demonstration of CDW based prefabricated elements).

In the following, inputs and outputs of CDE separation system (Figure 2.5) are briefly presented, while the methods to implement for materials processing will be subject of D2.3.

Figure 2.5: Input and output materials of CDE Global recycling plants.

a. *Preliminary step: Identification of structures to be demolished*

According to RE4 project needs and taking into consideration CDE contractors network, 4 different sources for C&D materials recovery have been identified. Both commercial and residential buildings have been selected, each of them from two EU sites (United Kingdom for north EU and France for south EU). The selected structures should be quite representative of different EU construction methodologies and architectural typologies.

b. Steps before CDE Global recycling facilities

The steps required before Construction and Demolition Waste (CDW) materials arrival at CDE recycling facilities include:

a) *Removal of hazardous materials* (i.e. asbestos, chemicals);
b) *Removal of cabling, copper*;
c) *Removal of usable materials to be separately recycled* (i.e. wooden materials, metallic beams, copper, plastics, plasterboard);
d) *Building demolitions*;
e) Removal of excavated soils and hard rubble;
f) *Collection of CDW*: the resulting unsorted materials (Figure 2.6) are collected and transported to CDE Global recycling facilities for treatment and processing.

Figure 2.6: Typical unsorted CDW as received by CDE Global.

c. *Inputs materials from CDE Global recycling plant*

Once the unsorted materials arrive at CDE Global recycling facilities the following steps need to take place:

g) *Removal of materials with size > 100 mm.* The current CDE system can process 0-100 mm materials, therefore materials with size > 100 mm are screened at the beginning of the process, often crushed and fed back into the system. These fractions are mostly made up of large solid parts (i.e. bricks, blocks, concrete).

h) *Removal of ferrous materials*. An over band magnet is integrated into a conveyor system and discharges the ferrous metals, which are sold to companies who recycle metals.

Figure 2.7: Over band magnet removes metals (a) and materials feeding (b) at CDE Global plant.

Summarizing, the typical materials feeding CDE separation system consist of:

- aggregates 4-100 mm (40-60% weight);
- sand 0-4 mm (30-50% weight);
- clay < 63 µm (10-20% weight);
- wood, plastics, other lightweights (e.g. organics, floating materials), metals (5-10% weight).

It can be observed that CDW fractions typically processed by CDE are mostly made of heavy materials (by concrete, blocks or bricks processing), the volume of fines (clay) can be 10-20% while the lightweight materials (i.e. wood, plastics, lightweights, metals) are very small.

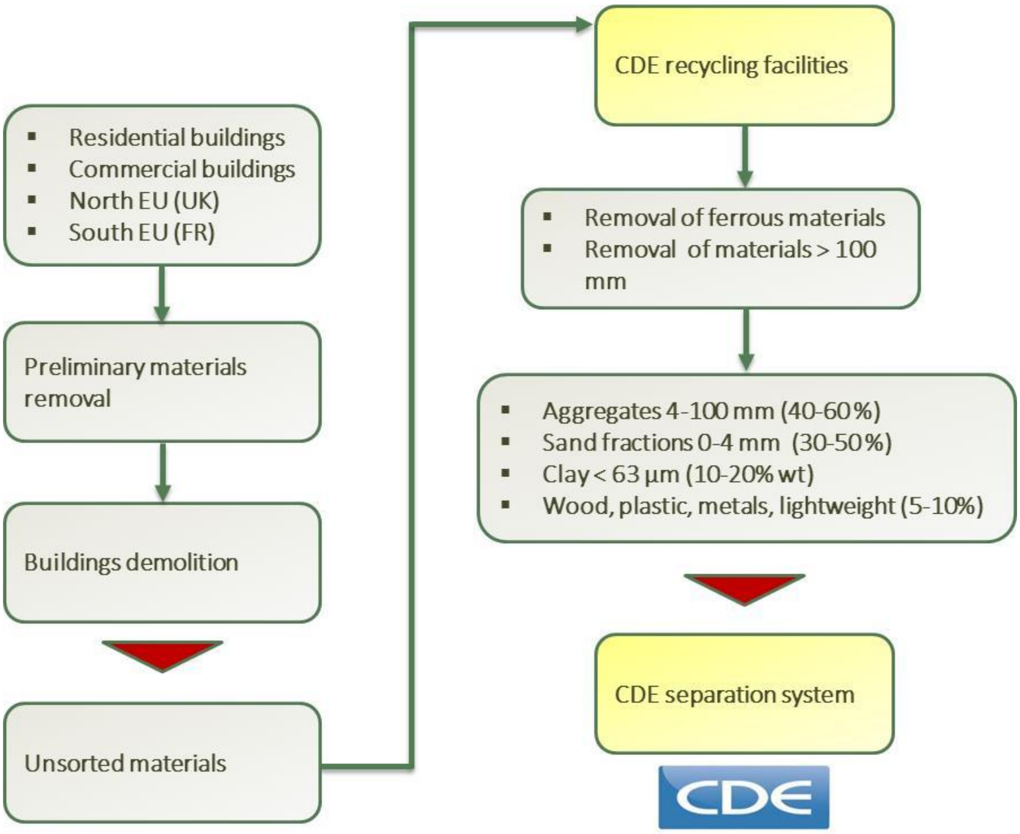


Figure 2.8: Flow chart reporting typical materials feeding CDE Global separation system.

d. CDE Global process

CDE Global has available recycling equipment solutions to process Construction and Demolition Waste (CDW). The current system can process 0-100 mm CDW and is specifically designed to cope with their dirty nature. The full description of CDE recycling process is beyond the scope of this document and will be detailed in a separate deliverable (D2.3).

e. Outputs materials from CDE Global recycling plants

Typical CDE outputs consist of mineral aggregates and sand. For RE[4] project also lightweight materials (i.e. plastics, wood), ceramics (i.e. bricks, tiles) as well as fine fractions (i.e. silt, clay) will find specific applications. Therefore, the CDW materials provided by CDE Global separation system include (Figure 2.9 and Figure 2.10):

- *heavy materials* (i.e. stones, tiles, bricks, glass; impurities such as plastic and wood should be in the range of 0.1% by volume) with 0-2, 2-8 and 8-16 mm sizes - intended as aggregates for concretes development, reconstituted tiles and, possibly, as alkali activated cement precursors. Elimination of possible organic impurities from fine fractions (0-2 mm) will be also investigated;
- *mixed lightweight materials* (i.e. wood, plastics and possible impurities such as polystyrene, organics and any other floating material) with 0-2, 2-8 and 8-16 mm sizes - intended as aggregates for lightweight concretes and insulating components;
- *silt and clay* < 0.063 mm - allocated to plasters and adhesives development. Effective test methods of separation of silt form clay will be also investigated.

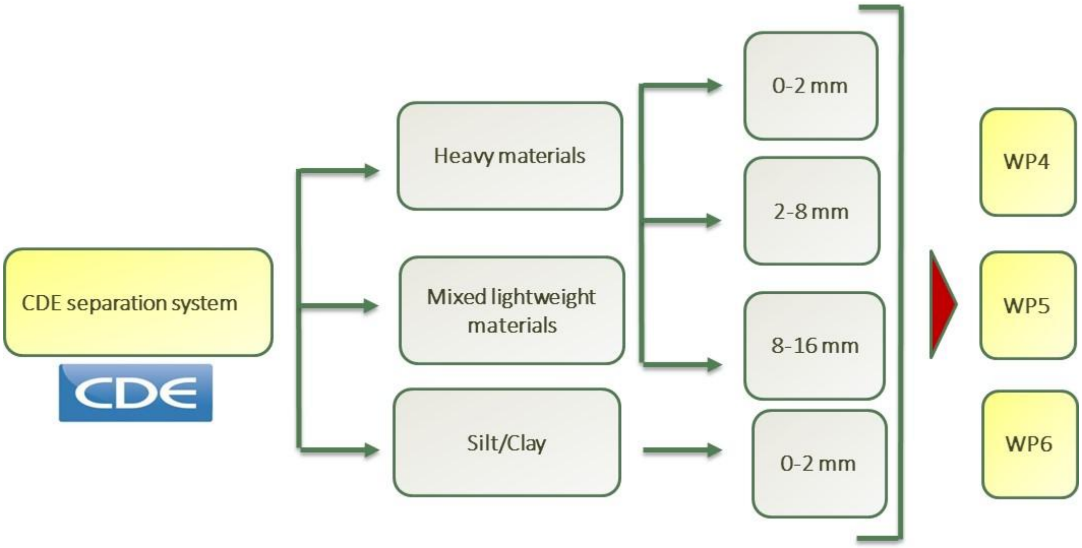


Figure 2.9: Flow chart reporting typical materials and sizes resulting from CDE Global separation system.

Figure 2.10: Typical output fractions resulting processing unsorted materials by CDE Global system: (a) C&D aggregates, (b) C&D sand (c) organic/lightweight mixed material, (d) silt/clay mixed materials.

f. CDE system error rate

Considering a typical volume of recycled heavy materials processed by CDE system (2-8, 8-16 and 16-32 mm as size range) it could be possible to find lightweight materials (e.g. wood, plastic), however the volume is very small and could be less than 0.1%. The error rate for lightweights and fractions < 0.063mm (silt and clay) from CDE systems is not known. These outputs, as above mentioned, are not separated further by CDE system at the moment.

CDE Global system will also provide input for the innovative Stam sorting system with the following fractions:

- *mixed heavy fractions* (including minerals, bricks, tiles etc.) with 16-32 mm size;
- *mixed lightweight fractions* (including wood, plastics etc.) with 20-80 mm size.

Input/output technical requirements of Stam sorting system will be detailed in section 4.3, while the methods to implement for materials sorting will be subject of D2.4.

3. Requirements for Stam sorting system input

To better understand the factors that will influence the output of CDE separating system, in Figure 3.1 a schematic vision of the RE4 project is shown. The square in the flow diagram boxes represent objects that are inputs or output of the red arrow-shaped boxes which represent systems that transform the inputs in outputs. In the previous section steps *a* and *b* were described; in the following, the other elements of the workflow are described, with particular focus towards the relationships between inputs and outputs and if there are particular assumptions or constraints to define the elements.

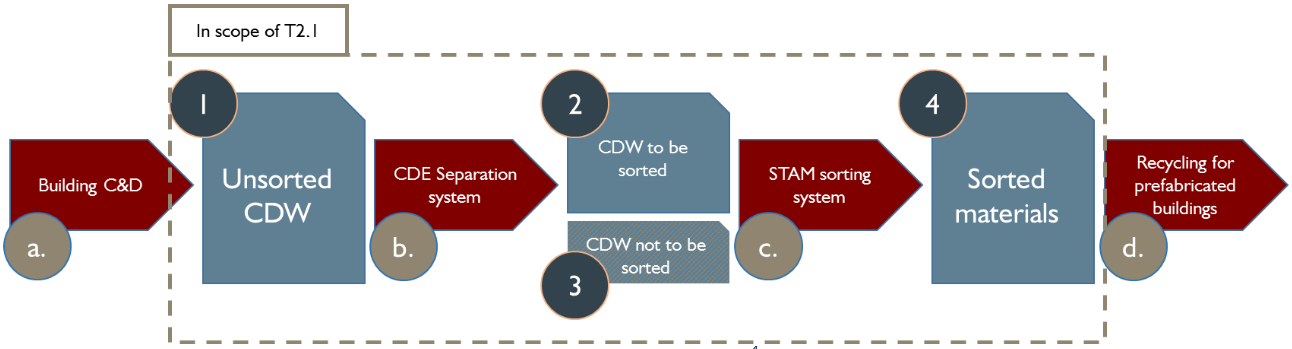


Figure 3.1: Schematization of the RE4 material flow

3.1. Material physical requirements and constraints

Within the material flow described in Figure 3.1, step *b.* (i.e. CDW to be sorted) takes place right before the sorting system and directly impacts the requirements for the design of the sorting system. In this framework, it is fundamental to exploit all the available information at this early stage of the project, to formulate meaningful, consistent requirements and constraints in order to have a solid base for the next phases.

The main goal of this section is the definition of the guidelines for material physical requirements, assumptions and constraints; to achieve this objective, two information sources will be studied:

- information from CDE about the separation system output;
- existing literature regarding building CDW.

At this stage of the Project broad categories of materials have been identified thanks to the project partners' expertise in CDW and indicative size ranges for fragments have been set. The fragments that will feed the automated sorting system will have the greatest dimension that ranges from 8 to 32mm.
It is worth noticing that while the lower range bound is mandatory (fractions under that size will not be sorted), the upper limit can be increased to a degree.
The materials into which CDW were grouped are an evolution of the materials described in section 2.1 and are:

- Bricks (full and not full):
- Tiles;
- Stone;
- Glass;
- Light Plastic;
- Heavy Plastic;

- Wood.

This information was then combined with existing CDW literature to have a baseline for materials' average distribution in CDW and their average density. The output of this study is presented in Table 1 that describes acceptable volume and weight ranges.
Volume range was calculated assuming that fragments are cubically-shaped with sides that range from 8 to 32 millimeters. The weight range was then calculated by multiplying the expected volume by the average density of each material.

Table 1 – Average fragments size and weight [4]

Material	Average density [kg/m³]	Size range [m³]	Weight range [kg]
Full bricks	2000	$5{,}12\cdot10^{-7}$; $3{,}28\cdot10^{-5}$	$1{,}024\cdot10^{-3}$; $6{,}553\cdot10^{-2}$
Non-full bricks	1000		$5{,}12\cdot10^{-4}$; $3{,}276\cdot10^{-2}$
Tiles	2000		$1{,}024\cdot10^{-3}$; $6{,}553\cdot10^{-2}$
Stone/mineral aggregates	2700		$1{,}382\cdot10^{-3}$; $8{,}847\cdot10^{-2}$
Glass	2400		$1{,}228\cdot10^{-3}$; $7{,}864\cdot10^{-2}$
Light Plastic	600	$8\cdot10^{-5}$; $5{,}12\cdot10^{-4}$	$4{,}8\cdot10^{-3}$; $3{,}072\cdot10^{-1}$
Heavy Plastic	1000		$8\cdot10^{-3}$; $5{,}12\cdot10^{-2}$
Wood	700		$5{,}6\cdot10^{-3}$; $3{,}584\cdot10^{-1}$

This information, despite its indicative nature, can represent a good starting point for the definition of the sorting system design. In fact, the assumptions made on materials physical properties (especially fragments size) make it not suitable to use existing solutions such as the one presented in [5] and designed by ZenRobotics and will require specific system design and integration.

Moreover, the assumptions made on materials physical properties can play a significant role in estimating the system's performance. To do so, the following formula can be used:

$$T\left[\frac{kg}{day}\right] = \frac{P_{hr} \cdot t_{op}}{\sum_{i=1}^{8} F_i^w}$$

Being:

- T the total system productivity measured in *kgs per day*;
- P_{hr} the number of picks per hour that can be performed by the robotic system;
- t_{op} the number of operating hours of the system;
- F_i^w the number of fragments for every *i-th* material group that can be calculated as:

$$F_i^w = \frac{W_{tot} \cdot p_i^{avg}}{w_i^{avg}}$$

[4] Data as retrieved from http://www.yourspreadsheets.co.uk/typical-weights-of-building-materials.html
[5] Resource Efficient Use of Mixed Wastes – Task 2 – Case studies. Deloitte Research Group. Technical Report

Being:

- W_{tot} the total weight of sorted materials [kg];
- p_i^{avg} the average weight percentage of the *i-th* material in CDW;
- w_i^{avg} the average weight of the *i-th* material fragment.

The reference values for p_i^{avg} and w_i^{avg} that will be considered to tune the other parameters (e.g. target operating hours and number of pick operations per hour) are shown in Table 2.

Table 2 – Material composition reference Values [6]

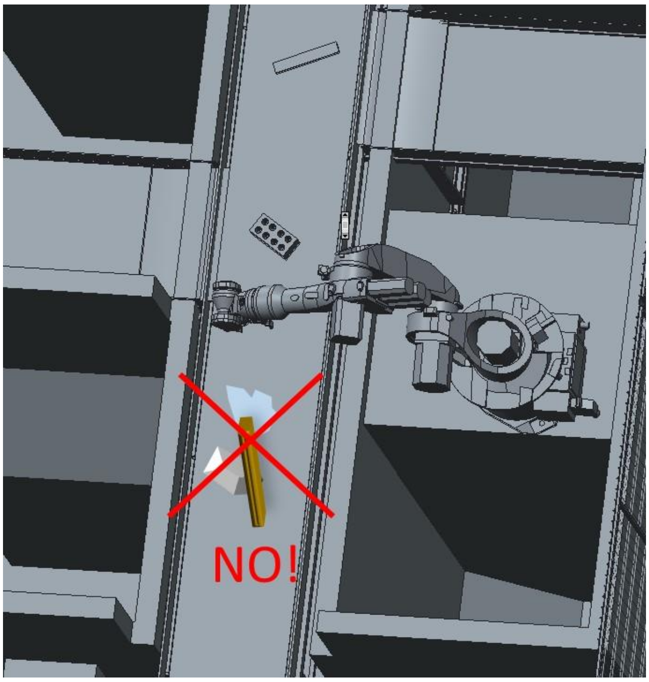
i Index	Material	Average percentage	Weight range [kg]
1	Full bricks	12,36%	$1{,}024\cdot10^{-3}$; $6{,}553\cdot10^{-2}$
2	Non-full bricks	25,75%	$5{,}12\cdot10^{-4}$; $3{,}276\cdot10^{-2}$
3	Tiles	17,82%	$1{,}024\cdot10^{-3}$; $6{,}553\cdot10^{-2}$
4	Stone/mineral aggregates	30,11%	$1{,}382\cdot10^{-3}$; $8{,}847\cdot10^{-2}$
5	Glass	0,14%	$1{,}228\cdot10^{-3}$; $7{,}864\cdot10^{-2}$
6	Light Plastic	0,12%	$4{,}8\cdot10^{-3}$; $3{,}072\cdot10^{-1}$
7	Heavy Plastic	0,12%	$8\cdot10^{-3}$; $5{,}12\cdot10^{-2}$
8	Wood	13,57%	$5{,}6\cdot10^{-3}$; $3{,}584\cdot10^{-1}$

3.2. Material interaction requirements

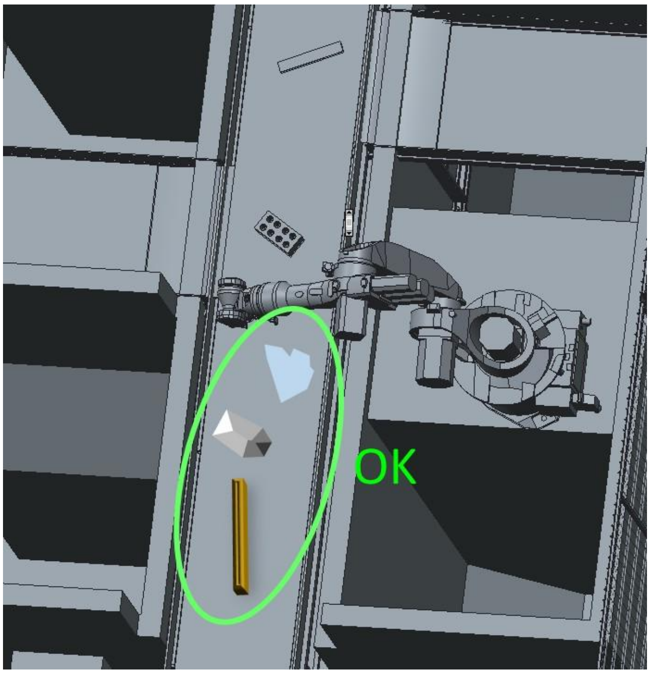
In order to allow the robot-based sorting system to properly manage and detect the different material typologies and, consequently, handle the pieces, the CDW has to satisfy some physical constraints in relation to their reciprocal positions on the feeding system and then on the main conveyor belt as explained in the concept design in Section 3.3.

These kinds of requirements are strictly related to the features of the sorting system. Indeed, the sorting procedure will be strongly based on the topology of the CDW parts on the belt, taking their shape and position as the first input from the sensors to properly calibrate the robot movements. Then, the position and contours of each object have to be well defined and distinguishable from each other, as shown in Figure 3.2.

[6] Franklin Associates, Characterization of building-related construction and demolition debris, The U.S. Environmental Protection Agency Municipal and Industrial Solid Waste Division Office of Solid Waste, 1998



(a)



(b)

Figure 3.2: Positioning on the belt - (a) wrong configuration with overlapped objects and (b) properly non-overlapped

The reason for such a requirement is mainly the fact that the robot end effector is thought to grip the CDW pieces one by one; moreover, it will come from above the conveyor belt, then operating on a 2D space in which the objects can be managed. Then, the parts to be sorted have to be clearly separated on the plane of the belt.

Actually, the robot movement algorithm would be even simpler if the orientation of the gripper isn't constrained, then a minor requirement is the presence of a minimum distance between each object, equal to the thickness of the end effector clamp (Figure 3.3).

In the case a vacuum suction end-effector will be finally chosen, the main constraint will be the minimum distance between the parts as the radius of the end-effector itself: indeed, the handler will be positioned on the center of the object to be picked, so no other pieces will be erroneously picked at the same time (Figure 3.3).

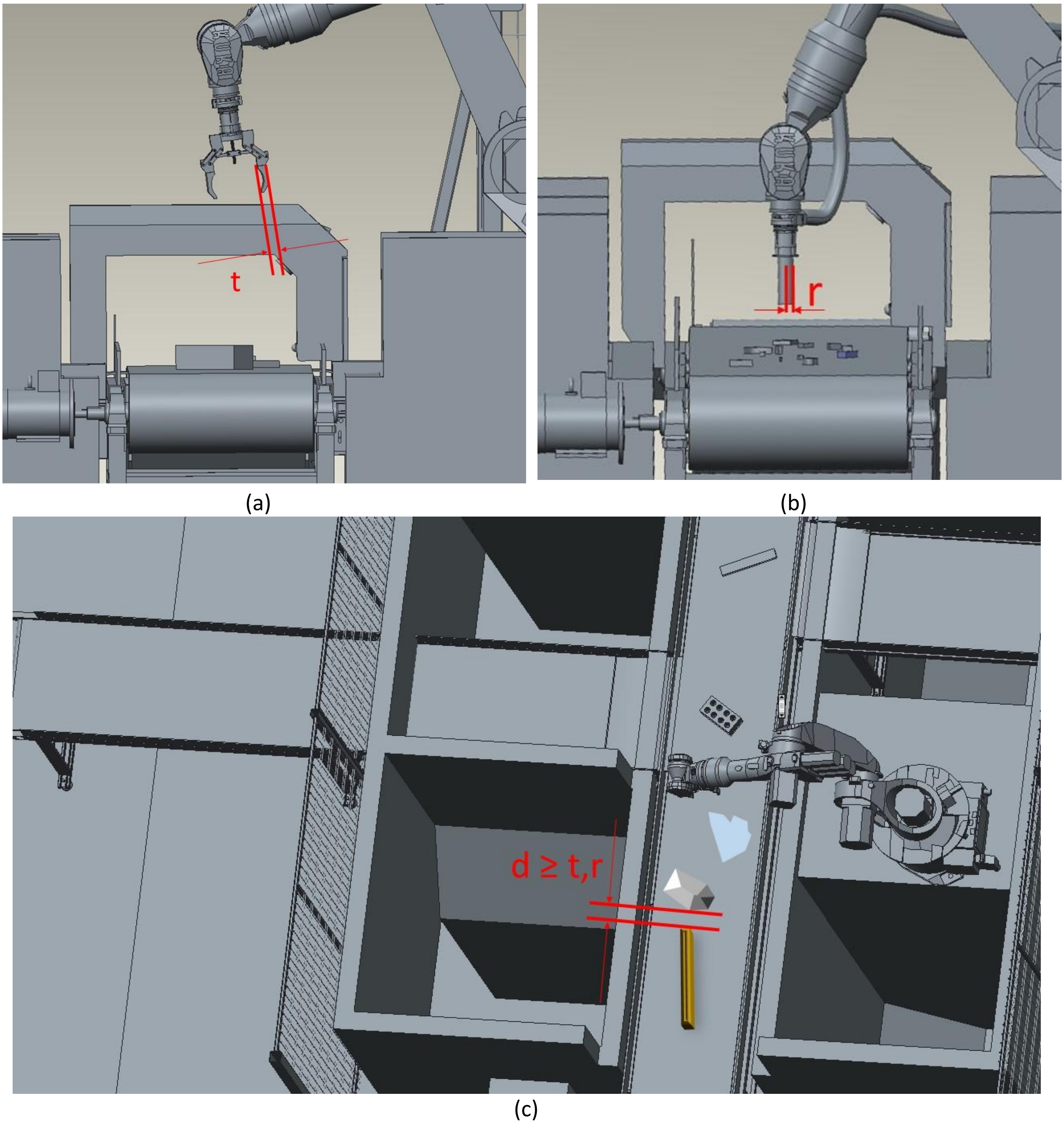


Figure 3.3: Constraints to positioning - (a) thickness and (b) radius of end-effectors; (c) distance between objects on the belt

Finally, no physical-chemical interaction is supposed to be between parts of different materials: if two or more different material parts were stuck together, it would be impossible for such a robotic system separating them.

Each exception from the above explained requirements will increase the error rate of Stam's sorting system.

3.3. Stam sorting system concept

It is the system responsible to further sort different materials as brick, tile, stone, glass, wood and plastic and therefore maximize the quality of sorted materials from CDW to be used in WP4, WP5 and WP6. The three main blocks of the system are:

- **Feeding Unit:** combination of conveyers and physical gates to filter the arriving unknown objects in terms of dimension and the distribution density across the conveyor.
- **Object recognition:** sensory system that identifies the objects type based on the signals coming from the different in-line mounted sensors and the trained real-time classification algorithm.
- **Object manipulation:** A six degrees of freedom robotic manipulator (Concept A, Figure 3.5) or a Cartesian robotic (Concept B, Figure 3.6) to move the end effector to the desired position. Grasping the object is done by a proper gripper to pick the identified objects and throw them in their corresponding storage space. The characteristic of the gripper is highlight dependent to the objects to be manipulated. Pictures below (Figure 3.4) illustrate the possible solutions:

(a) (b) (c)

Figure 3.4: Possible gripper solution - (a) five finger parallel gripper, (b) deformable jamming gripper, (c) sucking end effector

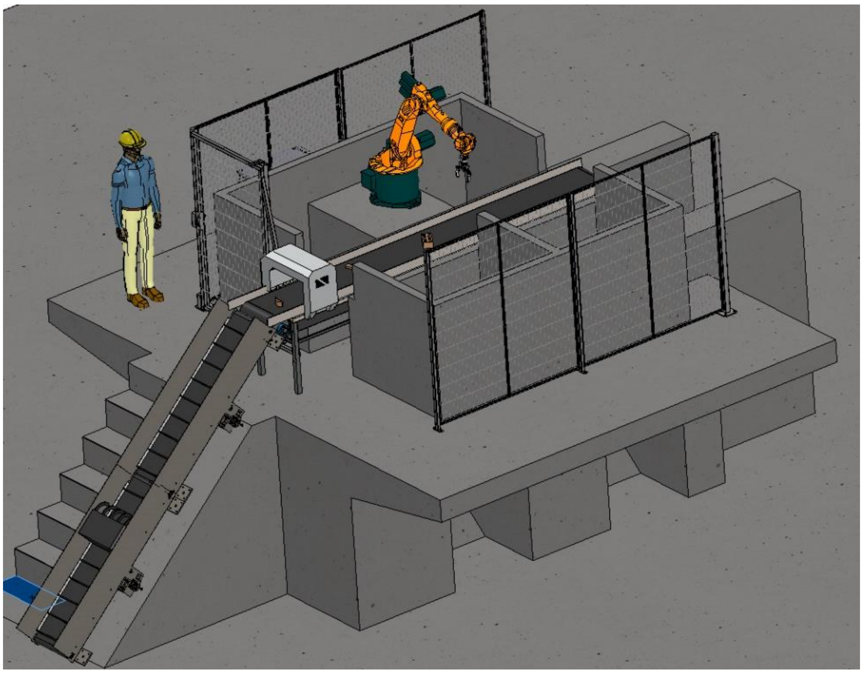


Figure 3.5: Sorting system concept A

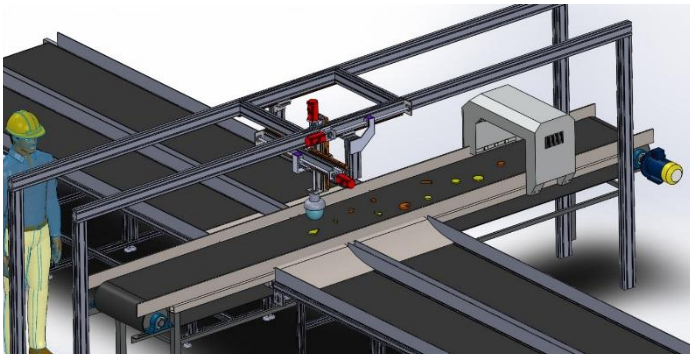


Figure 3.6: Sorting system concept B

- **Main control unit (MCU):** The master system that has to host the recognition and classification process of the sensory unit as well as motion planning to control the manipulator.

Sorted materials: The direct output of the sorting system will be sorted materials, which will be classified into the sorting sub-classes presented in Table 3.

Table 3 – Subdivision into weight-based classes and material classes

Class	Sorting sub-class
Lightweight Materials	Wood
	Plastics
Heavy materials	Glass
	Stone/mineral aggregates
	Tiles
	Bricks

3.4. Sorting system feeding rate

The feeding rate of the sorting system is constrained from its sub-systems which are the detection-classification phase and the object manipulation task. The parameter of tonnes per hour is used to measure the input to the sorting system. The already available commercial solutions in the market reach up to 98% of classification rate with picking rate of 2,000 kg/hrs. As the expected order of magnitude of the system productivity is of thousands of kilograms the minimum feeding rate cab be set as 100kg/hrs, assuming system operating time of at least 16hrs/day.
In the following a more detailed description of the mentioned involved sub-systems affecting the feeding rate is reported:

Objects detection sensory system & Classification algorithm: this subsystem is divided into two sequential processes of material detection and objects classification. The material detection has to satisfy real-time application requirements. This includes both sensory system spent time to return the filtered signals, plus the classification algorithm decision making time. The amount of time required by the classification process is the function of the algorithm model to be used and number of classes to be sorted.
The cutting-edge machine learning based classification algorithms will provide the advantage to convert a time-consuming classification algorithm into a real-time solution.

Motion planning and Objects pickup:

After mapping the materials flow in a 2D image, the motion planning algorithm calculates inverse kinematic solutions to approach the target object with right timing, position and orientation.

Accordingly, to the nature of the sorting flow, the master system has enough time from the recognition phase to the pickup moment to process and fulfill the pick-up task. The gripper design can simplify the motion planning process by eliminating object approach orientation constraints: this will be kept into account while performing detailed design of the robot as certain vacuum grippers can allow picking up objects even from the sides, which is going to release several trajectory planning-related constraints.

4. Technical requirements on output of Stam sorting system

As already seen for CDE separating system in Section 2, the main goal of the present chapter is the definition of the technical requirements for the CDW derived materials as output of the robotic sorting system that will be developed by Stam in Task 2.4, representing one of the main final output of WP 2 activities. The requirements are collected from different perspectives, including the material characterization which will be performed in WP 4, the prefabricated elements production in WP 5, and other intrinsic features referred to the robotic sorting system itself, such as the final sorting error rate according to the different applications in which the sorted materials will be adopted.

4.1. Sorted parts for CDW-derived materials development in WP4

WP4 aims to characterise unsorted mineral aggregates (heterogeneous mix of rock aggregates, masonry, ceramic and glass particles), sorted aggregates (different fractions of homogeneous material i.e. rock aggregate fraction and masonry-ceramics-glass fraction), lightweight fraction (mixed plastic and wood chips), fine material fraction (comes from the thickening of water used for material washing) and timber fraction (large pieces of timber).

Characterisation of unsorted mineral aggregates and sorted aggregates (rock aggregate fraction) will be performed by comparing their geometric, physical, chemical and durability properties obtained in accordance with National and European Norms and Standards. A preliminary list of tests was determined during the preparation of the proposal and reported here as follows:

Geometric testing will include:

- **Grading** (*in accordance with EN 933-1:2012* [7]). The test consists of dividing and separating an aggregate sample into several particle size classifications of decreasing sizes by means of a series of sieves. The aperture sizes and the number of sieves are selected based on the nature of the sample and the accuracy required. When washing can alter the physical properties of a lightweight aggregate, dry sieving is used. The mass of the particles retained on the various sieves is related to the initial mass of the material. The cumulative percentages passing each sieve are reported in numerical form or in both numerical and graphical form.
- **Flakiness index** (*in accordance with EN 933-3:2012 [8]*).The test consists of two sieving operations. Initially, the aggregate sample is separated into various particle size fractions d_i/D_i by using test sieves. Each of the particle size fractions d_i/D_i is then sieved using bar sieves which have parallel slots of width $D_i/2$. The overall flakiness index is calculated as the total mass of particles passing the bar sieves expressed as a percentage of the total dry mass of particles tested. If required, the flakiness index of each particle size fraction di/Di is calculated as the mass of particles passing the corresponding bar sieve, expressed as a percentage by mass of that particle size fraction.
- **Shape index** (*in accordance with EN 933-4:2008 [9]*).It is applicable to particle size fractions of d_i/D_i, where $d_i \geq 4$ mm and $D_i \leq 63$ mm. Individual particles in a coarse aggregate sample are classified based on the ratio of their length L to thickness E using a particle slide gauge. The shape index is calculated as

[7] EN 933-1:2012. Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution-Sieving method.
[8] EN 933-3:2012. Tests for geometrical properties of aggregates. Part 3: Determination of particle shape-Flakiness index.
[9] EN 933-4:2008. Tests for geometrical properties of aggregates-Part 4: Determination of particle shape-Shape index.

the mass of particles with a ratio of dimensions *L/E* greater than 3 expressed as a percentage of the total dry mass of particles tested.

- **Percentage of crushed or broken particles** (*in accordance with EN 933-5:1998 [10]*).It is applicable to gravel or mixed aggregate containing gravel with particle size fractions of d_i/D_i, where $d_i \geq 4$ mm and $D_i \leq 63$ mm. The test is carried out by sorting particles by hand, from a test portion of coarse aggregates into: (a) crushed or broken particles (including totally crushed or broken particles) and (b) rounded particles (including totally rounded particles). The mass of each of the above two groups is determined and expressed as a percentage of the test portion mass. Next, totally crushed or broken particles and totally rounded particles are sorted by hand from crushed or broken particles and rounded particles. Finally, the mass of each of these groups is determined and expressed as a percentage of the test portion mass.
- **Angularity of fine aggregates** (*in accordance with EN 933-6:2014 [11]*).It is applicable to coarse aggregate with particle sizes between 4 mm and 20 mm as well as fine aggregate of particle sizes of up to 2 mm. The flow coefficient of an aggregate is defined as the time (expressed in seconds) for a specified volume of aggregate to flow through a given opening, under specified conditions using a standard apparatus.
- **Shell content of coarse and all-in aggregates** (*in accordance with EN 933-7:1998 [12]*).It is applicable to gravel or mixed aggregate containing gravel with particle size fractions of d_i/D_i, where $d_i \geq 4$ mm and $D_i \leq 63$ mm. The test is carried out by sorting shells and shell fragments by hand, from a test portion of coarse aggregate. Next, the shell content is determined as the proportion of the mass of shells and shell fragments to the mass of the test portion. Finally, the shell content (*SC*) is expressed as a percentage.

<u>**Physical testing will include:**</u>

- **Resistance to fragmentation** (*in accordance with EN 1097-2:2010 [13]*).It is applicable to natural, manufactured or recycled aggregates used in Building and Civil Engineering.
- **Resistance to wear** (*in accordance with EN 1097-1:2011 [14]*).It is applicable to natural, manufactured or recycled aggregates used in Building and Civil Engineering. The method determines the micro-Deval coefficient which is the percentage of the original aggregate sample reduced to a size smaller than 1.6 mm during rolling. The aggregate sample is normally tested in a wet condition. However, the test may also be carried out in a dry condition.
- **Particle density and water absorption** (*in accordance with EN 1097-6:2013 [15]*).These tests will be carried on with a number of methods to determine the particle density and water absorption of normal weight and lightweight aggregates.

[10] EN 933-5:1998. Tests for geometrical properties of aggregates. Part 5: Determination of percentage of crushed and broken surfaces in coarse aggregate particles.
[11] EN 933-6:2014. Tests for geometrical properties of aggregates. Part 6: Assessment of surface characteristics-Flow coefficient of aggregates.
[12] EN 933-7:1998. Tests for geometrical properties of aggregates. Part 7: Determination of shell content-Percentage of shells in coarse aggregates.
[13] EN 1097-2:2010. Tests for mechanical and physical properties of aggregates. Part 2: Methods for the determination of resistance to fragmentation.
[14] EN 1097-1:2011. Tests for mechanical and physical properties of aggregates. Part 1: Determination of the resistance to wear (micro-Deval).
[15] EN 1097-6:2013. Tests for mechanical and physical properties of aggregates. Part 6: Determination of particle density and water absorption.

- **Loose bulk density** (*in accordance with EN 1097-3:1998 [16]*).It is applicable to natural and artificial aggregates up to a maximum size of 63 mm. The method is based on determining the dry mass of aggregates filling a specified container by weighing. Next, the corresponding loose bulk density is calculated.
- **Resistance to polishing** (*in accordance with EN 1097-8:2009 [17]*). A method for determining the polished stone value (PSV) of a coarse aggregate used in road surfacings will be used. The test is performed in two stages on aggregate passing a 10 mm sieve and retained on a 7.2 mm grid sieve. During the first stage of the test, aggregate samples are subjected to a polishing action using an accelerated polishing machine. In the second stage, the state of polishing reached by each specimen is measured by means of a friction test. Finally, the PSV is calculated from the above measurements. An optional method for the determination of the aggregate abrasion value (AAV) is also described in EN 1097-8:2009 [17]. This is used when particular types of skid resistant aggregates, which may be susceptible to abrasion under traffic, are required (typically those with a PSV ≥ 60).

Chemical testing will include:

- **Petrographic description** (*in accordance with EN 932-3:1997 [18]*).The standard procedure is not suitable for the detailed petrographical study of aggregates for specific end uses but it is only applicable to natural aggregates such as sand, gravel or crushed rock aggregate and their source materials.
- **Classification of the constituents of coarse recycled aggregates** (*in accordance with EN 933-11:2009 [19]*).The goal of these tests will be to identify and estimate the relative proportions of constituent materials in recycled coarse aggregate. The method consists of manually sorting particles from a sample of recycled coarse aggregate into a list of constituents. The proportion of each constituent in the sample is then determined and expressed as a percentage by mass (except for the proportion of floating particles which is expressed as a volume by mass).
- **Water-soluble chloride salts** (*in accordance with EN 1744-1:2009+A1:2012 [20]*). for the objective of this test will be to determine the water-soluble chloride salt content in aggregates.
- **Water-soluble sulphates** (*in accordance with EN 1744-1:2009+A1:2012* [20]). It consists of two different procedures for determining the water-soluble sulphate content in (a) natural and manufactured aggregates and (b) in recycled aggregates.
- **Carbonate content of fine aggregates for use in concrete surface courses**. This test will be carried out to assure that the carbonate content of fine aggregates to be used in concrete surface courses is compliant with EN 196-2:2013 [21] and the results declared.
- **Other constituents (i.e. organic matter which alter the rate of setting and hardening of concrete)** (*in accordance with EN 1744-1:2009+A1:2012 [20]*). It is a test for determining the potential presence of humus and a method for determining the fulvo acid content.

[16] EN 1097-3:1998. Tests for mechanical and physical properties of aggregates. Part 3: Determination of loose bulk density and voids.
[17] EN 1097-8:2009. Tests for mechanical and physical properties of aggregates. Part 8: Determination of the polished stone value.
[18] EN 932-3:1997. Tests for general properties of aggregates. Part 3: Procedure and terminology for simplified petrographic description.
[19] EN 933-11:2009. Tests for geometrical properties of aggregates. Part 11: Classification test for the constituents of coarse recycled aggregate.
[20] EN 1744-1:2009+A1:2012. Tests for chemical properties of aggregates. Part 1: Chemical analysis.
[21] EN 196-2:2013. Method of testing cement. Part 2: Chemical analysis of cement. British Standards Institution, London, 2013.

- **Other constituents (i.e. water-soluble components from recycled aggregates on the initial setting time of cement)** (*in accordance with EN 1744-6:2006 [22]*). It aims at determining the influence of water-soluble components from recycled aggregates on the initial setting time of cement.

Finally, durability testing will include:

- **Magnesium sulphate soundness of coarse aggregate (resistance to weathering)** (*in accordance with EN 1367-2:2009 [23]*). This test shows how an aggregate behaves when subjected to the cyclic action of immersion in magnesium sulphate, followed by oven drying.
- **Resistance to freezing and thawing** (*in accordance with EN 1367-1:2007 [24]*). This test determines how an aggregate behaves when subjected to the cyclic action of freezing and thawing. It is applicable to aggregates with particle sizes between 4 mm and 63 mm.
- **Volume stability-drying shrinkage** (*in accordance with EN 1367-4:2008 [25]*). The effect of aggregates on the drying shrinkage of concrete will be measured thanks to this test. It is applicable to concretes of fixed mix proportions and maximum coarse size aggregate of 20 mm. The aggregate under examination is mixed with cement and water and cast inside prism moulds of specified dimensions. The prisms are subjected to wetting followed by drying at 110 ± 5 °C. Next, the change in length from the wet to the dry state is determined. The excess drying shrinkage of the concrete is attributed to the aggregate and is expressed as a percentage of the average change in length of the prisms over the reference dry length.
- **Alkali-silica reactivity**: Verification of the potential reactivity of aggregates.

This list will be reviewed by WP4 partners prior to the start of activities and in case some of the tests will be deemed not to be relevant they will be excluded.

The current state of the art for utilising recycled aggregates in concrete is summarised by BS 8500-2:2015+A1:2016 [26], which is the complementary standard to EN 206:2013+A1:2016 [27] and distinguishes between two different types of coarse recycled aggregate:

- Crushed Concrete Aggregate (CCA) produced by crushing hardened concrete of known composition that has not been in use and has not been contaminated during storage or processing.
- Recycled Aggregate (RA) produced from demolition waste which contains concrete, masonry and asphalt.

The allowable limits of contaminants for the above two types of coarse aggregate (particle size ≥ 4 mm) are given in the Table below and can be used as preliminary guidance key performance indicators for the assessment of the RE4 Separation and Sorting Systems.

[22] EN 1744-6:2006. Tests for chemical properties of aggregates. Part 6: Determination of the influence of recycled aggregate extract on the initial setting time of cement.
[23] EN 1367-2:2009. Tests for thermal and weathering properties of aggregates. Part 2: Magnesium sulphate test.
[24] EN 1367-1:2007. Tests for thermal and weathering properties of aggregates. Part 1: Determination of resistance to freezing and thawing.
[25] EN 1367-4:2008. Tests for thermal and weathering properties of aggregates. Part 4: Determination of drying shrinkage.
[26] BS 8500-2:2015+A1:2016. Concrete-Complementary British Standard to EN 206. Part 2: Specifications for constituent materials and concrete. British Standards Institution, London, 2016.
[27] EN 206:2013+A1:2016. Concrete-Specification, performance, production and conformity.

Table 4 – Allowable limits of contaminants for coarse aggregates

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 content[28] (%)	Max. acid soluble sulphate (%)
CCA	10	4	2	5	1	0.8
RA	100	4	2	10	1	*

*To be determined on a case by case basis

Even if the maximum clay and masonry content is set at 10% due to the innovative nature of the RE4 project and for the higher quality of the materials the project is targeting the combined limit for impurities (materials other than mineral aggregate) should be set at 1%.

It is expected that Stam Sorting System (including crushing and sieving) should be able to provide the following size classes for rock aggregate fraction:

- 0-2 (mm)
- 2-8 (mm)
- 8-16 (mm)

It is also expected that Stam Sorting System should be able to provide coarse size rock aggregate fractions (2-8 (mm) and 8-16 (mm)) which contain less than 1% by mass of impurities (masonry, ceramics and glass), assuming that other impurities (such as metals, wood, plastic rubber and gypsum plaster) have already been removed by the CDE Separation System (in accordance with EN 933-11: 2009 [19]).

The masonry-ceramics-glass fraction obtained by the Stam Sorting System will be characterised for assessing its suitability as a precursor material in the development of geopolymer concrete. Its characterisation will be based on assessing its chemical properties by employing X-ray fluorescence (XRF) analysis, X-ray diffraction (XRD) analysis and Fourier transform Infrared (FTIR) spectroscopy. Compressive strength and workability of developed geopolymer concrete mixes will be used as performance indicators.

Stam Sorting System should also be responsible for separating plastics from wood chips when it comes to the lightweight fraction. Plastics and wood chips fractions will also be characterised as part of WP4 for their suitability in the production of insulation panels. Their characterisation will be based on assessing their geometric, physical and thermal properties (i.e. grain size, density, water absorption, thermal conductivity and heat capacity).

Fine material fraction which comes from the CDE Separation System (thickening of water used for material washing) will be characterised for assessing its suitability as filler, fine fraction for extruded products, plaster/adhesive, SCM or precursor for geopolymer reaction after calcination. Its characterisation will be based on assessing its physical and chemical properties by determining liquid and plastic limits and employing X-ray fluorescence (XRF) analysis, X-ray diffraction (XRD) analysis and Fourier transform Infrared (FTIR) spectroscopy. However, its production is not expected to be from Stam Sorting System.

[28] Clay, soil, metals, wood, plastic, rubber, gypsum plaster and glass.

Finally, physical characterisation of large pieces of timber which come from the CDE Separation System will be done by ROS.

4.2. Recycled materials for prefabricated components development in WP5

This chapter presents several inputs related to European standards and regulations regarding recycled materials and their use for the production of prefabricated elements. Although this is mainly related to WP4, it is key to start defining some basic requirements of the automatic sorting system by knowing the main quality requirements that sorted materials will have to comply with.

Specified prefabricated concrete elements and products are covered by harmonised European standards and are thus subject to CE-marking. However, prefabricated elements and products falling outside the scope of these specified harmonised standards cannot be CE-marked. For the standards treating prefabricated concrete elements which are issued by CEN/TC229 a lot of common features, such as material requirements, are put into a horizontal standard *EN 13369 - Common rules for precast concrete products*- to which reference is made in the different product standards. The latest edition of this standard was issued in 2013 to which an amendment was published in 2016. Due to the formalities of harmonised standards, which have to be announced in the European Official Journal, this latest edition is not yet in use since the existing harmonised standard makes reference to an earlier edition. However, since this project aims at the future, the requirements of the edition from 2013 will be treated here.

For the concrete material and its constituents reference is made to EN 206-1 *Concrete - Specification, performance, production and conformity* in EN 13369. However recycled aggregate is mentioned in EN 13369, but with the reservation "Alternative provisions are in development in the upcoming version of EN 206-1 and should be considered". (The upcoming version of EN 206-1 is the now existing EN 206:2013 amended 2016).

Three types of recycled materials are mentioned in both EN 13369 and EN 206. Two of these, reclaimed washed aggregate and reclaimed crushed aggregate, only consist of materials originating from the own factory. I.e. aggregates washed from the fresh concrete at the concrete/concrete element factory and crushed hardened concrete from the factory's own production, which has never been used in construction.
The third one is recycled aggregate, defined as "aggregate resulting from processing of inorganic materials previously used in construction". Only requirements regarding this third type will be included in this review.

What is then said about recycled aggregates in EN 13369? Only coarse recycled aggregate is mentioned. The aggregate size is designated in terms of lower (*d*) and upper (*D*) sieve size expressed as *d*/*D.* The definition of coarse aggregate in the existing aggregate standard (EN 12620+A1:2008) is "aggregate with *D* greater than or equal to 4 mm and *d* greater than or equal to 2 mm". Briefly, it is specified that the recycled coarse aggregates shall not adversely affect the setting and hardening of the concrete and its durability: pure concrete debris may be used if the source and mix proportions of the concrete is known, in amounts up to 10% of the total amount of aggregate in the mix if the requirement on strength of the new concrete is fulfilled. Up to 20% may be used if the mechanical strength of the source concrete is tested and the strength of the new element is verified by full scale testing. Higher amounts postulate that in addition to these requirements, all the relevant properties of the hardened source concrete shall be known.

Moreover, recycled aggregate should not be used in concrete for which durability requirements are higher than those for the concrete from which the recycled aggregates originate. This is however not required for concrete in exposure classes X0, XC1 and XC2, which encompasses most indoor concretes. X0 is used for concrete which does not contain reinforcement or metal or in very dry environment. XC1 is a dry or constantly wet environment and XC2 is a wet and seldom dry environment. If theses exposure classes are the major environmental attack, it presupposes that there shall be no exposure to chlorides from sea-water or other sources, and no exposure to freezing and thawing or attack by aggressive chemicals.

In EN206, the provisions for recycled aggregate are more general. Instead of relying on knowledge of the source concrete as in the provisions in EN 13369, classification is carried out according to the concrete aggregate standard, EN 12620, relying on sorting and classification of the crushed recycled construction products, which is not only concrete. Since this standard is harmonised, the coarse recycled aggregate shall be CE-marked.

For the classification, according to EN 12620 the coarse recycled aggregates shall be examined for the purpose of identifying and estimating the relative proportions of the constituent materials according to EN 933-11 *Tests for geometrical properties of aggregates - Part 11: Classification test for the constituents of coarse recycled aggregate.*
Floating particles, FL, are estimated by volume and the following constituents by weight:

- Rc: Concrete and mortar
- Ru: Unbound aggregate and natural stone
- Rb: Clay and calcium silicate masonry units, aerated non-floating concrete
- Ra: Bituminous materials
- Rg: Glass
- X: Other, such as clay and soil, metals, non-floating wood, plastic and gypsum

EN 12620 then specifies classes for the content of these constituents to be used for declaring the constituents of the recycled coarse aggregate.

Other properties that should be declared are:

- Grading;
- Chloride content;
- Sulphur containing compounds;
- Influence on the initial setting time of concrete;
- Particle density and water absorption;
- Water soluble sulphates.

The concrete standard EN 206 recommends that also the fines content, the resistance to fragmentation and the shape of coarse aggregate should be declared.
EN 12620 does not give any maximum or minimum requirements for these properties.
However, EN 206 gives recommendations in an informative annex (E) regarding requirements for these properties for recycled coarse aggregates to be used in concrete. They propose a separation into two classes, Type A and Type B, with different requirements.

Type A shall have a particle density of at least 2100 kg/m^3 and should consist of ≥ 90% Rc and ≥ 95% Rc + Ru, ≤10% Rb, ≤ 1% Ra, ≤ 2% FL and ≤ 2% X + Rg.
Type B should have a particle density of at least 1700 kg/m^3 and should consist of ≥ 50% Rc and ≥ 70% Rc + Ru, ≤30% Rb, ≤ 5% Ra, ≤ 2% FL and ≤ 2% X + Rg.

Normally used sieve sizes for separating coarse aggregate for concrete into grading sizes are 2; 4; 8, 11.2 (12); 16; 20 and 32 mm.

When it comes to using these types of recycled aggregates in concrete, the recommended allowed amount depends on the exposure class of the concrete in which it shall be used, i.e. what kind of environmental influences the concrete will be subjected to. For the most severe environments, as for example in concrete subjected to severe freezing and thawing when water-saturated and/or exposed to sea-water or de-icing salts it is recommended to not use recycled coarse aggregates at all. In the mildest environment, indoors in a very dry environment (X0) up to 50% of the coarse aggregate can be recycled aggregate of Type A or B, according to the recommendations in EN 206. For exposure classes between these extremes 30% of type A may be used. Type B may, in addition to X0, only be used in those classes slightly more exposed or susceptible to carbonation (XC1, XC2) with an amount up to 20%. Use of Type B is also restricted to lower strength classes ≤ C30/37 (compressive strength in MPa).

Note that the percentages are given as percent of the coarse aggregate, not of the total aggregate content. 50% of the coarse aggregate, which normally constitutes around 50% of the total aggregate content in concrete, entails that the maximum amount would be 25% of the total aggregate content. For a normal concrete this entails that the maximum allowed recycled aggregate is around 20% of all dry concrete constituents. The values of 30% and 20% of the coarse aggregate leads go 12% and 8% respectively of the dry concrete constituents.

This is far from the goal of this project, which is to reach a much higher percentage of recycled aggregate in precast concrete elements. In addition to trying to investigate the use of higher percentages of coarse recycled aggregate than recommended today, particularly for concrete in the least severe exposure classes. (X0 and XC1) other options to increase the amount in concrete has to be looked at.

The fine fraction (0 - 2 mm), i.e. filler aggregates, of the recycled aggregate is not specifically mentioned, neither in the aggregate standard, EN 12620, nor in the concrete standard, EN 206. Thus, no specific rules for this are given but there are not any prohibitions either. A possible interpretation of this may be that if the recycled filler aggregate fulfils the same requirements as filler aggregates of natural aggregate, they may be used in the same way. The requirements on the fine aggregate or filler is mainly chemical requirements, such as maximum amount of chlorides, sulphur and sulphates and restriction of constituents which alter the rate of setting of the concrete.

Crushed particles are normally more water-demanding than natural sand particles, which makes the concrete harsher and may increase the amount of cement needed to obtain the required strength. The change of the water demand in comparison to the use of natural sand should be investigated. There is no standardized method for this. A simple method, elaborated for crushed natural fine aggregate in could be used to evaluate this property. The principle of this method is that a mortar with fixed w/c-ratio (0,58) and fixed proportions between the volume of the paste and volume of the aggregate (0,6/0,4) is mixed and put into a Hägermann cone and then the flow of the mortar is measured.

Another possible property of the filler fraction of recycled aggregate that may be taken advantage of is that the finest fraction may contain very fine particles (≤ 0,063 mm) that may be reactive to some extent (primarily cement), and contribute to the strength of the concrete elements. They would then act as a reactive addition (Type II according to EN 206), like ground granulated blast furnace slag or fly ash that can replace some of the cement content. This is outside the scope of any standard today, but the possibility could be investigated. The reactivity (activity index) for this material may be determined in the same way as for slag or fly ash.

4.3. Stam sorting system input & output requirements

The output materials of CDE system, consisting in mixed heavy fractions with 16-32 mm size and mixed lightweight fractions with 20-80 mm size, will be in this phase of the process furtherly sorted in order to separate the mixed fraction in more specific classes of materials.

In particular, in this phase, from the **heavy mixed mineral fraction** the rocks, bricks, tiles or ceramics and glasses will be sorted. The residual materials of the mixed mineral fraction will be the residual impurities from CDE systems (< 1% in weight). As far as it concerns dimensions, the sorted materials will be furtherly crushed and sorted in size in order to obtain the desired fractions. For the purpose of the Project, materials will be classified in the following three classes 0-2 mm, 2-8 mm and 8-16 mm (Figure 4.1).

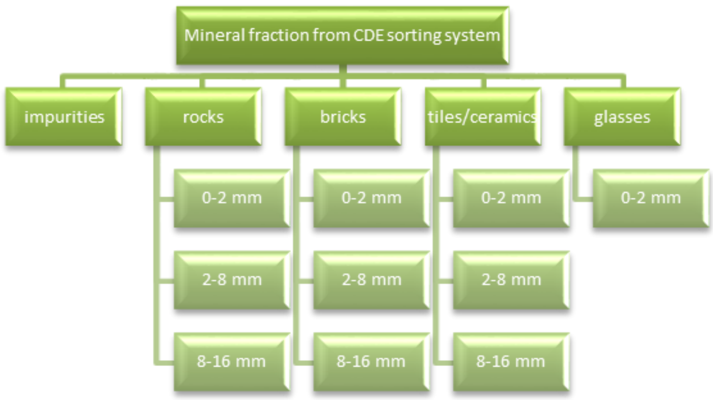


Figure 4.1: Different materials coming from CDE mineral fraction after the employ of STAM sorting system

Considering the **lightweight fraction** of C&D waste, Stam's sorting system will provide a separation of wood and plastic from the recovered materials from the cleaning water phase of CDE system. Such materials will enter Stam's system after been first dried and then sorted (Figure 4.2) in terms of:

- materials, separating wood and plastic,
- dimensions, different classes of size will be present in the incoming materials.

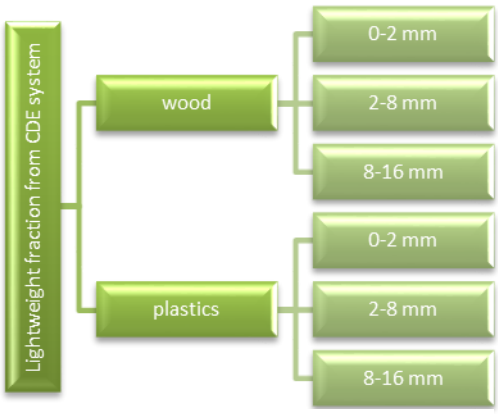


Figure 4.2: Lightweight materials sorting specification

Moreover, the possibility of sorting the wood by shape (chips or fibres) will be studied.

The residual materials of the lightweight fraction entering the Stam system will hence be impurities like organics (e.g. grass) and polystyrene.

As far as it concerns dimensions, the sorted materials will be furtherly crushed and sorted in dimension in order to obtain the desired classes. In particular, the materials will be classified in the same three classes 0-2 mm, 2-8 mm, 8-16 mm, as the mineral aggregates.

4.4. Stam system error rate

In previous sections of the deliverable, several parameters regarding materials types, size, weight and distribution were described. These were used to deduce requirements and constraints for the robotic sorting system that will be developed in Task 2.4.
A further step towards the definition of requirements and specifications for the sorting system is to determine the system's accepted error rate.

In order to do that, mainly two parameters were kept into:

- Material composition tolerances for reuse applications;
- Percentage of CDW used for the application.

Regarding material composition tolerances, it is a parameter highly dependent on the reuse application. This means that existing standards or guidelines are to be considered. Table 5 shows the possible application described in the DOW for each sorted material class which will be addressed by Stam robotic sorting.

Table 5 – Material class application from DOW

Material	Description	Possible application
Sorted aggregate	Sorted aggregates with classed sizes	Structural concrete for load bearing prefabricated element
Ceramic material	Bricks, tiles, other ceramics	Geopolymer binder, supplementary cementitious materials, reconstituted tiles
Plastic	Mixed plastics aggregates with classed sizes	Lightweight concrete for prefabrication, insulating prefabricated panels
Wood	Broken and chopped wood	Insulating prefabricated panel

Concrete production is the only application that presents well established rules and best practices. For the other applications, as part of the project research will focus on the development of technical documentation for the products developed, pointing out the most suitable certification strategies and standardization of innovative tests as well as the formulation of materials with a high level of CDW incorporation and development of precast elements and components from these materials.

As most of the applications do not have precise standards due to the undefined production processes and material mixtures that will be developed during the project, the main limitation will come from concrete production regulations, which is going to be used as a baseline for the definition of an acceptable error rate range.

Regarding concrete a commonly accepted convention is the one used in [29], that divides recycled aggregates into three main types:

- Type I: Aggregates which are implicitly understood to originate primarily from masonry rubble;
- Type II: Aggregates which are implicitly understood to originate primarily from concrete rubble;
- Type III: Aggregates which are implicitly understood to consist of a blend of recycled aggregates and natural aggregates.

[29] Alan S. De Venny, Recycling of demolished masonry rubble, School of the Built Environment Napier University, 1999.

With regards to these aggregate types also draws up several specifications regarding maximum allowable values for impurities in recycled aggregates for concrete production. These specifications are reported in Table 6.

Table 6 – Classification of recycled coarse aggregates for concrete

Mandatory requirements	Type I	Type II	Type III
Max. content of material with density≤2200kg/m^3 (%)	-	10	10
Max. content of material with density≤1800kg/m^3 (%)	10	1	1
Max. content of material with density≤1000kg/m^3 (%)	1	0,5	0,5
Max. content of foreign materials (glass, bitumen, soft materials etc.)	5	1	1
Max. content of organic material (%)	1	0,5	0,5

In order to have a safe and conservative range, the worst possible case is analyzed to make sure that even in that scenario the system performance is guaranteed. This happens when the material with the lowest acceptable percentage and the highest density (i.e. Glass) is picked in the form of fragments with the highest possible size. The maximum content of soft materials can be translated into number of wrong picks as:

$$P_g \leq P_a \cdot \frac{W_a}{W_g \cdot 99}$$

where P_g is the number of picked parts of glass, P_a is the number of picked fragments of sorted aggregates, W_a is the average weight of a part of aggregate and W_g is the average weight of a part of glass.

By substituting values from Table 1 into the formula, the accepted error rate in terms of number of picks is roughly 1.15%.

Moreover, from the DOW it is stated that the produced components will feature a minimum of 30% of recycled materials. Considering the minimum contribution of recycled materials, the maximum error rate that can be accepted in order to guarantee that the produced elements are in line with generally accepted standard is 3.8%. This value is not intended as a strict requirement as it is based on the only application for sorted materials that presents sound literature and commonly accepted best practices. Since the other material classes will be investigated in terms of requirements during further phases of the project the value obtained for concrete production can be taken as a general reference and state that a maximum error rate of 5% by weight is generally accepted. During the design of Stam robotic system, information exchange between Task 2.4 and WP4 and 5 will be key to tune this parameter depending on the detailed requirements that will come up.

5. Conclusions

The present deliverable is an analysis of the technical requirements of separating and sorting systems which will be developed within RE^4 project. These requirements were collected and defined according to the Project purposes declared in the Grant Agreement, together with the status of the art on building materials, with main reference to the four typologies that were identified for the studies within this project: Northern and Southern Europe, residential and non-residential buildings.

In particular, CDE's separating system is expected to get as input a mixture of different CDW derived components (mainly concrete, bricks, glass, metals, wood, plastics and organic materials, in many different size fractions. This first separating system will remove every part with size larger than 100 mm, together with metallic parts, and will separate heavy materials (stones, tiles, bricks, glass and heavy impurities) from lightweight materials (wood, plastics and impurities) and fine fractions (silt and clay) assuring a level of contamination between lightweight materials and heavy materials ≤0.1% in terms of volume.

Referring to Stam's robotic sorting system, it will be aimed at the development of two different classifiers for heavy and light materials, in order to have a final differentiation into stone, tiles, bricks, glass, plastic and wood. The entering pieces are expected to range between 8 and 32 mm of size, while the output materials will be divided into three fractions being 0-2 mm, 2-8 mm and 8-16 mm, respectively. Moreover, the entering parts will have to be well dry and physically separated on the conveyor belt feeding the robotic system, in order to let the classification algorithm and the sensors work properly. The final goal for the contaminants presence by weight in the output batches will be set to 1% and in terms of robot picks error rate the maximum allowable percentage was estimated around 4%.

All the outcomes of Task 2.1 described in this report will be used as reference in the following of the WP 2 activities of RE^4 project, in particular for *Task 2.3 Innovative strategies and processes for separating CDW based on weight criteria* and *Task 2.4 Innovative strategies and processes for sorting CDW based on advanced robotic system*.

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