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Refractory Sorting Using Revolutionizing Classification Equipment

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WP 4 Preparation for sorting

D4.3 Preliminary flowsheet design

ReSoURCE

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Executive Summary

The preliminary flowsheet of the Demonstrators is defined, and the expected mass flows are calculated. The formative decision to be done for the preliminary flowsheet was to exclude electrodynamic fragmentation as comminution process between Demonstrator A and Demonstrator B. The final flowsheet needs to be developed till M42. Developing the final flowsheet requires to evaluate and optimize the mass flows through the Demonstrators after experimental validation. The work reported in this deliverable refers to ReSoURCE project (*Resource - Refractory Sorting Using Revolutionizing Classification Equipment*) in the framework of WP4 – Preparation for sorting.

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1. Introduction

The handling and sorting of the received spent refractories is divided into two separate processes. For each part, a Demonstrator is developed, in the following referred to as Demonstrator A and Demonstrator B. The material flow starts with the refractory breakout, undergoing sieving and is then either sorted in Demonstrator A (5 – 120 mm), or processed in Demonstrator B (< 5 mm). This deliverable reports the preliminary flowsheet design of both Demonstrators.

Demonstrator A is designed as mobile solution, while the decision of having a mobile character for Demonstrator B is still under discussion, considering the lower maturity of level of the equipment. The mobile solution is realized using standard freight containers, which would in future also allow the processing to take place on-site, where the refractory breakout material is generated. The use of mobile equipment offers several benefits in general: it reduces the off-site plant infrastructure complexity, minimizes material shipment by bringing the processing equipment to the material, and ultimately reduces CO_2 emissions associated with transport.

D4.3 "Preliminary flowsheet design" is structured into the following chapters:

1. **Introduction**
   This section explains the rationale for having two demonstrators.
2. **Expected Input Mass and Material Description**
   This section provides details on the input mass and material handled by the demonstrators.
3. **Basic Concept of the Demonstrators**
   This section outlines the components of the demonstrators.
4. **Preclusion of electrodynamic fragmentation (EDF) as comminution process**
5. **Conclusion**

The main difference between the preliminary flowsheet and the final flowsheet is that the preliminary one is based on calculations, while the D4.4 "Final flowsheet design" (M42) will be using experimentally derived mass flows and parameters after the demonstrators have been constructed and validated.

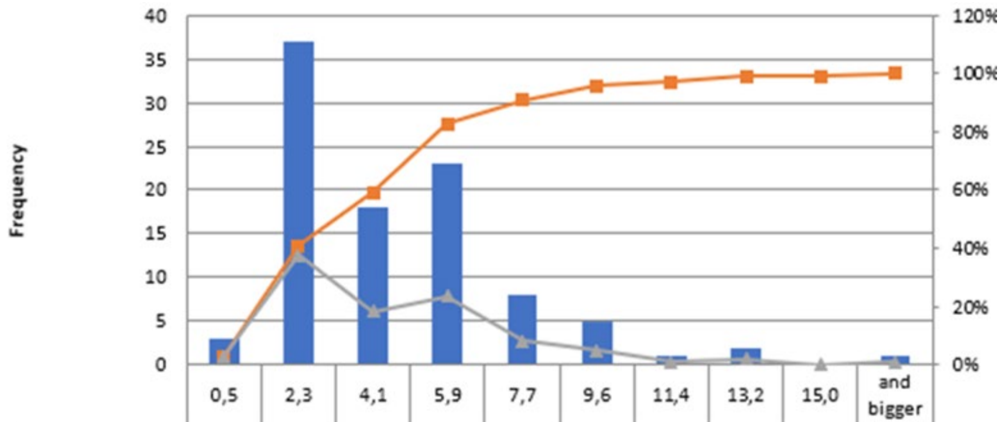
2. Expected input mass and material description

Following the comprehensive material characterization conducted in work package 3, focusing on sample batch CRK 1 (cement rotary kiln), insights into the expected input mass can be derived from D3.3. The characterization of hand-sorted refractory material, representing the currently sortable fractions, has provided data on weight classes and particle size distributions to be used in this evaluation of input mass.

Based on the results from D3.3 (see Figure 1), it is determined that 9% of the feed material comprises oversized particles, necessitating sieving, and thereby discharging this fraction from the process to comminute it to a sortable particle size. Additionally, the lowest weights class needs to be addressed, particularly if it contains particles smaller than 5 mm, as Demonstrator A is not capable of handling this fraction. If such material was present, this fraction (<5 mm) would need to be sieved out initially. Consequently, 91% of the breakout material of CRK 1 can be processed by directly sorting it with Demonstrator A.

Undersized material must be discharged from the process at the beginning using a sieve, while the 9% oversized material requires sieving, crushing, and reintroduction to the process. This can be realized through a crushing & sieving cycle, ensuring that particles within the correct size range are sieved out and reintegrated into the sorting process to prevent generating an excessive volume of fines.

To optimize the process and ensure the particle size range is narrow enough for the robot to sort, specific particle size classes need to be introduced (see chapter 3).



	0,5	2,3	4,1	5,9	7,7	9,6	11,4	13,2	15,0	and bigger
Frequency	3	37	18	23	8	5	1	2	0	1
Cumulated %	3%	41%	59%	83%	91%	96%	97%	99%	99%	100%
Non-Cum %	3%	38%	18%	23%	8%	5%	1%	2%	0%	1%

Figure 1: Histogram of weight classes (upper weight limit) for the qualified sample CRK , determined in WP3.

The <5 mm input fraction is processed in Demonstrator B to be sorted to different particle compounds depending on the refractory breakout input of Demonstrator A (CRK, SCL).

3. Basic concept of the demonstrators A & B

Overall Concept

Demonstrator A is capable of operating with a throughput of an average 5 t/h, handling particles ranging from 5 mm to 120 mm. It integrates three different sensors: LIBS (Laser-Induced Breakdown Spectroscopy), HSI (Hyperspectral Imaging) and a 3D camera. To facilitate sorting of the particles, robots are utilized for handling large and medium grain sizes, while an air ejection unit is employed specifically for sorting smaller grain sizes.

An exemplary particle size distribution of the feed for Demonstrator A (as outlined in chapter 2) could be represented as follows:

Table 1: Exemplary grain size distribution.

Particle size class [mm]	Mass [%]
5 – 30	20
30 – 80	40
80 – 120	40
Sum	100

Demonstrator B will be capable of handling a throughput of maximum 800 kg/h, with a particle size ranging from 0-5 mm. It is designed to handle pre-classified leftover refractory material <5 mm. The demonstrator will have a flexible design, where a selected material stream can be analysed using LIBS. The material will be sorted in different size classes using different sorting methods such as sieving or direct sorting. The demonstrator will be used for research purposes to optimize the sorting and handling of leftover material before further recycling steps.

Two examples of the particle size distribution of the feed either coming from CRK or SCL (steel casting ladle) for Demonstrator B (described in chapter 2, and analysed in work package 1 & 7), could be illustrated as follows:

Table 2: Exemplary composition of Demonstrator B feedstocks from cement or steel industry.

Refractory breakout	Particle size class [mm]	Mass [%]
SCL	0 - 1	50
	1 - 3	42
	3 - 5	8
Sum		100
CRK	0 - 1	34
	1 - 3	47
	3 - 5	19
Sum		100

Material pre-processing:

The main pre-processing is crushing of oversized material and sieving (illustrated in Figure 2) to obtain the required grain fractions on which the demonstrators will be optimized.

- *Crushing:* Based on trials and liberation analysis carried out in the course of this work package three crusher types (jaw crusher, cone crusher and impact crusher) were evaluated, indicating beneficial characteristics generated by the jaw crusher. Crushing is employed to eliminate oversized particles (>120 mm), which are screened out at a first sieving step. The crushing process should be designed as a closed-loop comminution cycle, incorporating the sieve (120 mm) to optimize energy consumption, mitigate over-crushing, and minimizing the generation of fines.
- *Sieving:* Conducted to attain the processable grain size range. Demonstrator A requires a range of +5 mm to -120 mm, whereas Demonstrator B operates in particle sizes below 5 mm.
  For the optimized operation (e.g. settings of the air ejection) of the sorting system, the coarser fraction 5 – 120 mm will undergo further separation into three different particle size classes to be processed in Demonstrator A:
    a. 5 - 30 mm
    b. 30 - 80 mm
    c. 80 - 120 mm

  Note, that these ranges are subject to change depending on results obtained during the start-up phase. A reduction to two different grain sizes ranges would simplify the required infrastructure and will therefore be investigated.

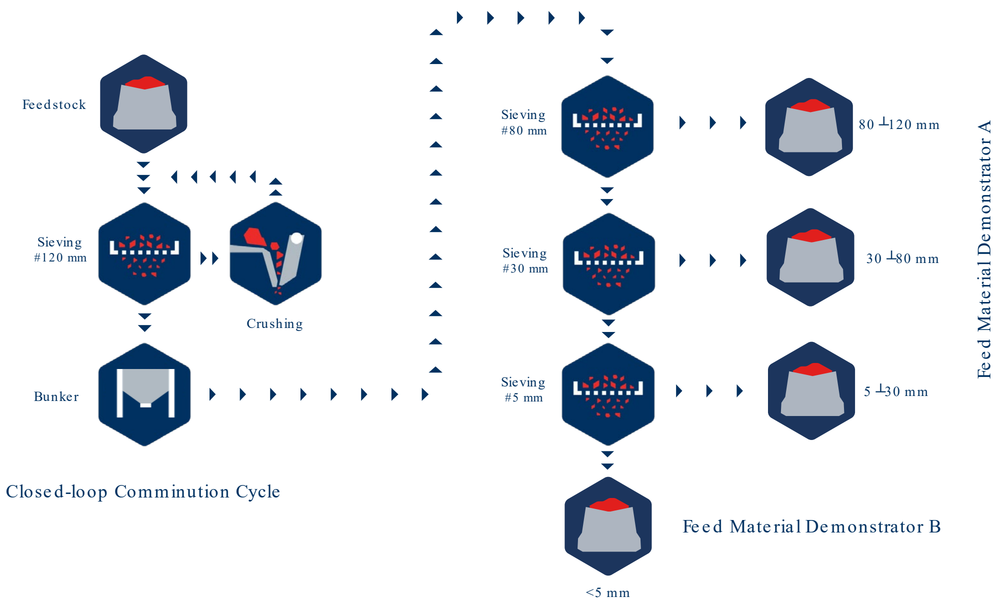


Figure 2: Material pre-processing steps before entering demonstrators.

Process Flow Demonstrator A (illustrated in Figure 3):

- *Material Handling and Singularization:* Batch-wise filling of the bunker, which can hold approximately 3.5 m³ of material, is carried out using a wheel loader. The bunker is designed to accommodate about 1.2 times the capacity of a wheel loader shovel. This ensures that the sorting process can proceed continuously without interruption during loading. Vibrations, which could negatively impact particle tracking in the second container, are prevented by fully decoupling the two containers. Feed material from the bunker is then continuously transferred via a vibration feeder onto a conveyor belt (acceleration belt). This setup increases the spacing between individual particles, making them easier for robots to grip or for air ejection nozzles to remove. To ensure the decoupling, the material is transferred to a second belt passing through the second container. By adjusting the vibration feeder parameters, using chain curtains, and varying the speeds of the two conveyors, the crucial step of singularization can be optimised.

- *Sensor Classification:*
  The singularized feed is transported on the second conveyor belt, passing under the measurement bridge responsible for object classification and relaying this information to the subsequent ejection devices. First, the 3D camera detects the objects, providing data on their position on the belt and material topography. Combined with hyperspectral imaging (HSI), which follows the 3D camera, the system intelligently pre-selects Regions of Interest (ROIs) based on the geometry information from the 3D sensor and/or spectral data from the HSI for real-time Laser-Induced Breakdown Spectroscopy (LIBS) analysis as the next step. After the LIBS measurement, all sensor data is processed to make a classification decision, which is then forwarded to the ejection units. Post-sorting, chemical and mineralogical information for each particle will be available, potentially aiding in quality assessment. The system undergoes calibration beforehand, using previously characterized bricks and employing Artificial Intelligence (AI). This calibration process lays the foundation for subsequent sorting operations.
- *Ejection*: Each robot has 4 different mini bins available, featuring a volume of roughly 400 l. The installed robots have different payload limitations that need to be considered. One robot is capable of handling bricks weighing up to 12 kg, while the other one is limited to 8 kg (a third robot can be added to the process at a more advanced stage of the project). The robot with the higher payload has a slightly reduced ejection frequency. These robots can be considered the bottleneck of the system in most scenarios dealing with large grain sizes, limiting the overall throughput in the process. Material not handled by them will be separated by air ejection into bins, being sorted into two products and a reject fraction. Eventually, sorted classes will be stored in steel bins which can be manipulated by a forklift to empty them at their final storage location at the recycling center.
  Table 2 gives an overview of expected shares of materials in different grain sizes handled by the individual ejection devices. Note, the additional spit at 50 mm, which is currently assumed to be the threshold grain size for using the robot ejection, guaranteeing the targeted machine throughput.

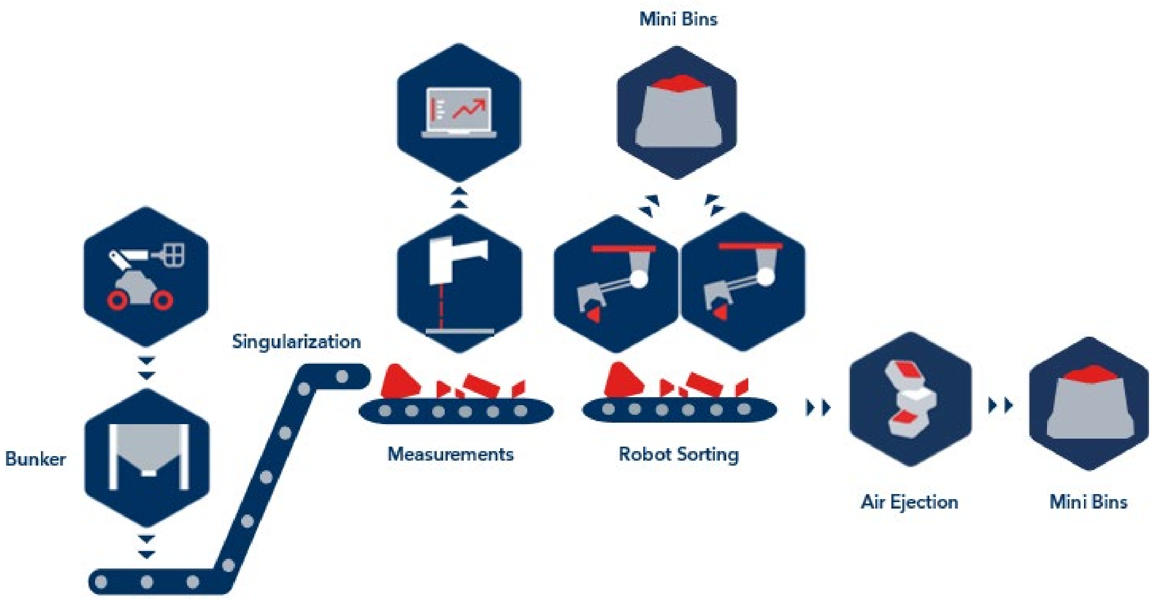


Figure 3: Process scheme of Demonstrator A.

Table 3: Expected distribution of the particle sizes handled by the different ejection devices.

Collecting bin	Particle size class [mm]	Mass [%]
1st Robot	50 – 80	10
	80 – 120	60
2nd Robot	50 – 80	25
	80 – 120	20
3rd Robot	50 – 80	25
	80 – 120	20
Air ejection unit	5 – 30	100
	30 – 50	100
	50 – 80	40
Sum	5 – 30	100
	30 – 50	100
	50 – 80	100
	80 – 120	100

Process Flow Demonstrator B:

- *Material Handling and Sieving:* Previously screened material (0-5 mm) is fed into a hopper from a big bag. The material is then conveyed from the hopper to a sieve using a screw feeder, where it is separated into two distinct fractions and transported to storage container. Diverter valves are installed on all material streams leading to a storage container. These valves offer the flexibility to either direct the material towards dedicated storage units or allow it to continue along the processing line right away.
- *Direct Sorting:* The fine material <1 mm is further transported to a direct sorting unit designed to further categorize the material into a fine and a coarse fraction. The coarse fraction from

the direct sorting unit is collected in a storage container. The emerging fine fraction is transported pneumatically to a cyclone and collected in a storage container. The air outlet from the cyclone will be directed through a filter to prevent loss of fine particles.

- *LIBS classification and sorting:* Material from the various storages can be transported to the LIBS measurement system integrated into the processing line for analysis and further sorting. In an alternative processing route, fractions may bypass direct sorting and proceed directly to the LIBS module for chemical analysis. Based on the measurement data obtained, a mechanical flap is installed to divert the material into two separate storage units, allowing concentration or depletion of certain components in the final material stream.

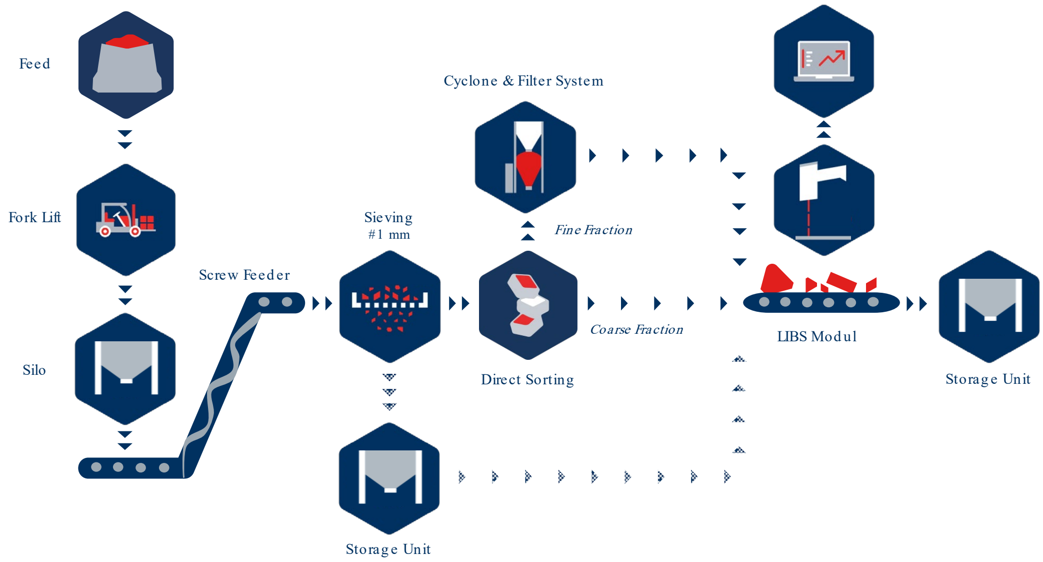


Figure 4: Process scheme of Demonstrator B.

Possible Processing of Reject Fraction:

While Demonstrators A and B are designed as independent units and are not initially intended to be linked as sequential processing steps, there remains the option to combine them by further processing the reject fraction of Demonstrator A.

Based on the fed particle class size, the air ejection and the robots in Demonstrator A will have a combined operating mode. The air ejection system has three outlets – two fractions of sorted material, each assigned with one or more specific sorting classes, and one reject fraction. The reject fraction may contain varying materials due to the precedent sorting process:

It can possibly contain material, that

- was not accurately measured and thus could not be assigned to a sorting class. A measurement error can occur, for example, due to material movement while passing under measurement bridge, misdirected laser measurement or the presence of dust as well as major contaminations on the particle surface.
- shifted on the belt and therefore could not be located by the robot.

- could not be gripped by the robot or dislodged after gripping, occurring due to irregular particle shapes or inadequate adhesion properties.
- was not handled by the robots because of a size below 50 mm (limit for robots) and does not belong to the fractions designated for the air ejection bins (robots have four bins to be assigned with different sorting classes).
- Small fragments emerging from wear and impacts during loading of the hopper.

Although this material is directed to the reject bin, it still holds potential for further sorting. After initial experimental assessments, a deeper understanding of the material composition of the reject material can be obtained. Following that, additional investigations can be conducted to explore potential solutions for its processing. A possible option could be to reprocess the rejects in Demonstrators A and B, based on particle size fractions.

Additionally, there will be genuine reject material in this bin, that is not sortable because it may be too fine or, based on chemical analysis, cannot be allocated to any specific sorting class. Thus, this material might need to be landfilled or utilized within non-refractory products developed in work package 9.

As mentioned above, another aspect to be considered for the reject fraction before reintroducing it to either Demonstrator A or B, is the generation of fines during material handling in bunker and conveyer belt transfer points due to abrasion. Consequently, there is a possibility that the feed material for Demonstrator A (+5 mm – 120mm) may contain fines. This necessitates subjecting all collected rejects, regardless of the feed material fraction, to an additional sieving step. This ensures the separation of the material into feed material suitable for Demonstrator A and B, depending on particle size requirements.

4. Preclusion of electrodynamic fragmentation (EDF) as comminution process

Work package 4 “Preparation for sorting” aimed to compare different comminution technologies. The four comminution technologies investigated in this work package were jaw crusher, impact crusher, cone crusher as conventional methods, as well as electrodynamic fragmentation (EDF) on lab-scale and EDF on semi-industrial scale as alternatives. The comminution efficiency of all procedures is evaluated and compared in D4.1 and D4.2, with the objective to assess whether one of those process would bring favourable characteristics in terms of grain liberation, size distribution or grain shape.

The idea to investigate EDF as a comminution step, reducing particle size after Demonstrator A to <5 mm, was based on the theory that the use of EDF might result in a higher degree of liberation than conventional comminution technologies. As the liberation experiments with EDF did not indicate sufficient levels of liberation, it was decided to exclude it from the processes to be realized within the demonstrators, especially considering the integration of a wet process like EDF would result in the necessity of additional aggregates (EDF, a drying process and wastewater treatment), requiring a third demonstrator, being out if scope this specific project. Based on this evaluation and considering findings of work package two, clearly showing a significant environmental impact by adding a drying step, EDF will not be used as comminution technology in the developed process chain in ReSoURCE.

5. Conclusion

The handling and sorting of spent refractories have been effectively divided into two distinct processes, each represented by a dedicated Demonstrator. Demonstrator A handles particle sizes between 5 mm and 120 mm, while Demonstrator B processes particles smaller than 5 mm. This bifurcation allows for targeted processing strategies optimized for each size range, maximizing the valorisation of the feedstock material.

Demonstrator A, designed as a mobile unit utilizing standard freight containers, offers several advantages, such as reducing off-site infrastructure complexity and minimizing CO_2 emissions by enabling on-site processing. Its mobile nature facilitates the direct handling of refractory breakout material, enhancing operational efficiency. The system integrates advanced technologies like Laser-Induced Breakdown Spectroscopy (LIBS), Hyperspectral Imaging (HSI), and 3D cameras for precise sorting and classification. The use of robots and air ejection units ensures effective sorting of both large and small particles, respectively.

Demonstrator B, though still under discussion for its mobility, focuses on finer materials. It features a flexible design for research purposes, allowing for the optimization of sorting and handling of leftover materials before further recycling steps. With a throughput capacity of up to 800 kg/h, Demonstrator B uses various sorting methods such as sieving and direct sorting, and incorporates LIBS for detailed chemical analysis.

A critical aspect of the process is the material pre-processing, which includes crushing and sieving to achieve the required grain fractions. This step ensures that oversized materials are appropriately reduced, and fine materials are segregated, allowing for efficient subsequent processing. The detailed evaluation of comminution technologies led to the exclusion of electrodynamic fragmentation (EDF) due to its insufficient liberation levels and significant environmental impact.

Overall, the preliminary flowsheet design sets the stage for the final design, which will be based on experimentally derived mass flows and parameters. The systematic approach adopted in this project, including the integration of advanced sorting technologies and comprehensive pre-processing strategies, ensures a robust and efficient recycling process for spent refractories. The anticipated benefits include improved material handling, reduced environmental impact, and enhanced quality assessment capabilities, laying a strong foundation for future advancements in refractory recycling.