EU Horizon program: Horizon-CL4-2021-TWIN Transition
Reducing environmental footprint, improving circularity in extractive and processing value chains (IA)
Refractory Sorting Using Revolutionizing Classification Equipment
Grant Agreement No 101058310

WP 4 Preparation for sorting
D4.4 Final flowsheet design

ReSoURCE

Project Reference No	101058310
Deliverable	D4.4 Final flowsheet design
Work package	WP4
Type	R
Dissemination Level	PU
Date	November 2025
Status	Final
Editor(s)	Karl Friedrich, Christina Poelzl, Alexander Leitner, Simone Sedlacek, Stefan Heid, Helmut Flachberger, Kristin Søiland, Chandana Ratnayake, Markus Dargel, Volker Moerkens, Milutin Bjelic
Contributor(s)	MUL, RHIM, SINTEF, LSA
Reviewers	All partners
Document description	This deliverable reports the final flowsheet design of Demonstrator A and Demonstrator B

Document revision history

Version	Date	Modification introduced	
		Modification reason	Author
V1.0	08.04.2025	1st version	MUL
V2.0	28.04.2025	2nd version	MUL
V3.0	28.11.2025	3rd version	MUL

Executive Summary

The final flowsheet of the Demonstrators A (RAPTOR) and B (PHOENICS) has been developed following an iterative experimental validation and a comprehensive evaluation of the associated mass flows. This flowsheet reflects an optimized process configuration for the recycling of spent refractory materials, ensuring efficiency in material handling, separation, and recovery. The work reported in this deliverable refers to ReSoURCE project (*Resource - Refractory Sorting Using Revolutionizing Classification Equipment*) in the frame of WP4 – Preparation for sorting.

The finalized flowsheet integrates improved comminution and sorting steps, supported by validated mass flow data, to achieve enhanced material liberation and minimized fine generation. This final configuration marks a significant milestone in the ReSoURCE project, delivering a robust and data-driven framework for sustainable refractory recycling, ready for future deployment, further evolvement into a scaled solution and further demonstration activities beyond the overall project lifetime.

Table of Contents

1. Introduction

The handling and sorting of the received spent refractories is divided into two separate grain size dependent pathways with underlying optimized beneficiation processes. For each grain size stream, a demonstrator was developed, in the following referred to as Demonstrator A (RAPTOR) and Demonstrator B (PHOENICS). The material flow starts with the refractory breakout, undergoing sieving as classification step and is then either sorted into the Demonstrator A path (5 – 120 mm), or processed into the Demonstrator B path (< 5 mm), see Figure 1. This deliverable reports the final flowsheet design of both Demonstrators.

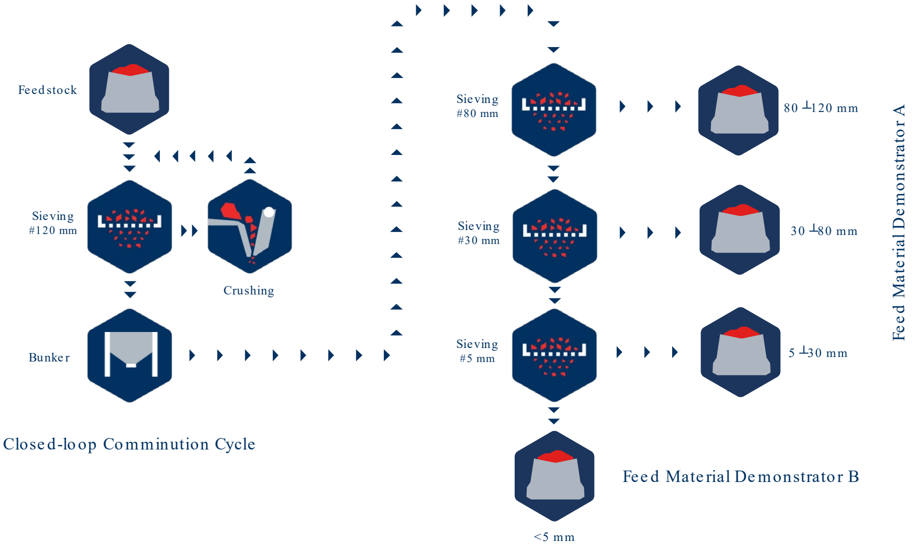


Figure 1. Material preparation steps before entering Demonstrators.

Both demonstrators have been designed as mobile, containerized solutions within standard freight containers. This approach enables future use of advanced, containerized sorting units that can be shipped directly to sites where refractory breakout occurs, reducing the need for extensive and costly material transport. Since the system is already designed as a complete solution for recycling and sorting refractory breakout, the need for additional standalone equipment at the breakout sites is greatly reduced. This lowers overall CO_2e emissions and improves the utilization of the demonstrators.

D4.4 “Final flowsheet design” is structured into the following chapters:

1. Introduction
   This section explains the reasoning for having two distinct pathways (A and B)
2. Expected Input Mass and Material Description
   This section provides details on the inputs and material handled by the demonstrators
3. Finalized Concept of the Flowsheet
   This section outlines the grouped parts of the flowsheet
4. Further Implementations and adaptations
   This section outlines future possibilities and adaptations
5. Conclusion

The key difference between the preliminary and the final flowsheet design lies in the level of data validation and technical certainty. The preliminary flowsheet (D4.3) is primarily based on theoretical calculations and assumptions regarding process performance and material behaviour. It served as an early conceptual framework to guide system setup and anticipate operational requirements. In contrast, the final flowsheet (D4.4), developed by M42, is built upon experimentally derived mass flows and process parameters, which are collected after the demonstrators have been constructed, commissioned and validated.

2. Expected input mass and material description

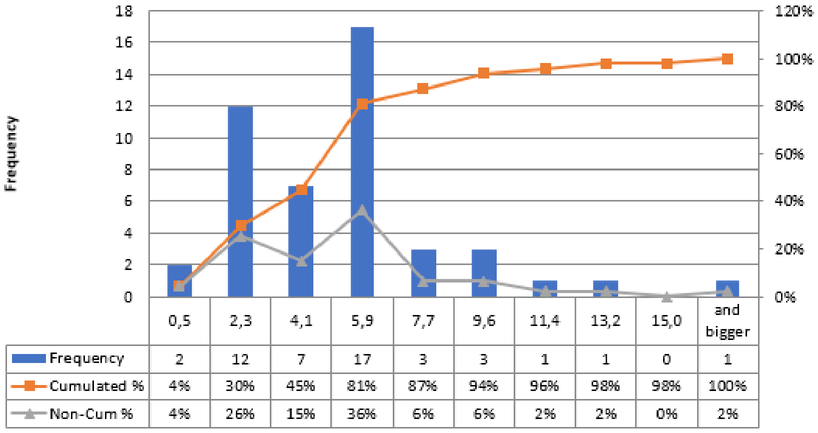
Following the comprehensive material characterization conducted in WP3, focusing on sample batch SCL (steel casting ladle) and CRK (cement rotary kiln), insights into the expected input mass can be derived from D3.3. The characterization of hand-sorted refractory material, representing the currently 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 for SCL (Figure 2Figure 2) and CRK (Figure 3), it is determined that about 9% (6.5% for CRK) of the feed material consists of oversized particles. These require an initial sieving step as the first classification and protection measure. The oversized fraction is removed from the process, further comminuted to a sortable particle size, and then reintroduced.

On the other side of the curve, the fraction 0–0.5 cm and below must be scalped and directed to a suitable beneficiation route, as Demonstrator A cannot handle fines below 5 mm efficiently.

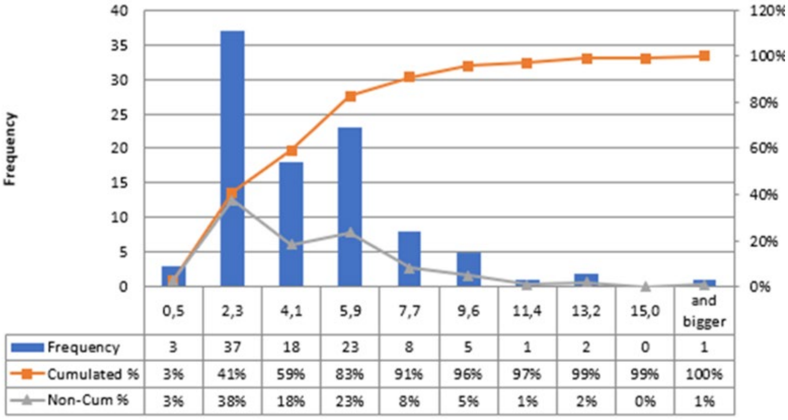
In summary, about 91% (93.5% for CRK) of the refractory breakout material from SCL can be processed directly in Demonstrator A. Around 5% (3.5% for CRK) requires additional comminution to reach a size suitable for Demonstrator A. The fraction below 5 mm, representing roughly 4% (3% for CRK) of the total mass, must be routed to Demonstrator B.

Demonstrator B, being the established approach for beneficiation of the <5 mm fine fraction, is responsible for sorting these fines into enriched compound fractions that can be transformed into marketable products.



	0,5	2,3	4,1	5,9	7,7	9,6	11,4	13,2	15,0	and bigger
Frequency	2	12	7	17	3	3	1	1	0	1
Cumulated %	4%	30%	45%	81%	87%	94%	96%	98%	98%	100%
Non-Cum %	4%	26%	15%	36%	6%	6%	2%	2%	0%	2%

Figure 2: Histogram of weight classes (upper weight limit) for the qualified sample SCL, determined in WP3



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

3. Finalized concept of the Flowsheet

Material pre-processing and preparation

The main preparation of material is an initial crushing of oversized material and sieving (illustrated in) to obtain the required grain fractions for which the demonstrators were designed for.

- Crushing: Based on trials and liberation analysis carried out during this WP, three traditional crusher types (jaw crusher, cone crusher and impact crusher) were evaluated, indicating beneficial characteristics generated by the jaw crusher. The crushing is designed in a circuit configuration together with a sieve at 120 mm, fixing the upper grain size of the subsequent material stream and eliminating oversized particles (>120 mm). With this circuit, overall energy consumption of this comminution step can be reduced to a minimum, avoiding overcomminuting of particles smaller than 120 mm and reducing the generation of fines.
- Sieving: To achieve suitable grain size fractions as feedstock, multiple sieves are set up in series to produce the needed inputs for Demonstrator A and B. Demonstrator A requires the larger size fraction from +5 mm to -120 mm. Demonstrator B operates with the extracted fines in the range 0 mm to -5 mm. As not all grains within the Demonstrator A pathway are extracted from the stream with the same ejection method, the grain size range is further split into three subdivisions
    a. 5 - 30 mm
    b. 30 - 80 mm
    c. 80 - 120 mm

  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.

Overall Concept after preparation

Demonstrator A operates with an average throughput of 5 t/h, handling grains ranging from +5 mm to -120 mm. It integrates three different sensors, which generate data necessary for the decision of subsequent sorting: LIBS (Laser-Induced Breakdown Spectroscopy), HSI (Hyperspectral Imaging) and a 3D camera. Based on the decision made, large to medium sized particles are extracted with installed robotic arms, while an air ejection unit is used for the sorting of the smaller grains

Exemplary particle size distributions of the feed for Demonstrator A (as outlined in chapter 2) for SCL and CRK are represented in Table 1.

Table 1: Exemplary grain size distribution of Demonstrator A feedstocks from SCL and CRK

Particle size class [mm]	Example Mass fraction SCL [%]	Example Mass fraction CRK [%]
5 – 30	30	15
30 – 80	50	40
80 – 120	20	45
Sum	100	100

Demonstrator B has a throughput of 0.8 t/h, handling grains ranging from 0 to -5 mm. The demonstrator is intended to handle the fines of the feedstock breakout refractories and has a purposefully designed flexibility in operation, in order to be optimally used in spite of higher variability within the fines of the feedstock and more complex conveying of material within the equipment. As sensor for sorting, LIBS is used for online analysis. Internally, the material is classified into different size classes using different classifying methods such as sieving or the multi-chamber fluidised bed separator.

Exemplary particle size distributions of the feed for Demonstrator B (as outlined in chapter 2) for SCL and CRK are represented in Table 2.

Table 2: Exemplary grain size distribution of Demonstrator B feedstocks from SCL and CRK

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

Process Flow Demonstrator A (illustrated in Figure 4)

- Material Handling and Singularization: Batch-wise filling of the bunker, which can hold approximately 3.5 m^3 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. 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, 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 collecting bins available, featuring a volume of roughly 400 l. The installed robots have different payload limitations that need to be considered. One installed robot (“1st robot”) can handle bricks weighing up to 12 kg, while the other one is limited to 8 kg (“2nd robot”). A third robot can be added to the process at a more advanced stage of the project. The 1st 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 centre.

Table 3 gives an overview of expected shares of materials in different grain sizes handled by the individual ejection devices. Note, the additional split at 50 mm, which is currently assumed to be the threshold grain size for using the robot ejection, guaranteeing the targeted machine throughput.

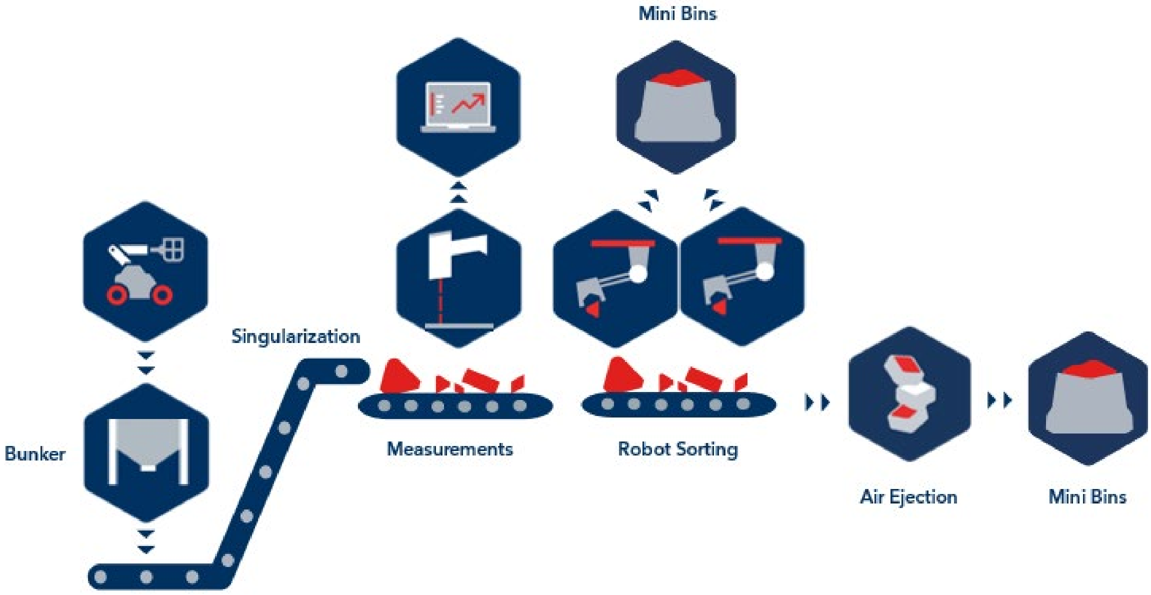


Figure 4: Process flow of Demonstrator A.

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	50
	80 – 120	40
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 (illustrated in Figure 5)

- Material Handling and Sieving: The feedstock from the initial material preparation (0 to -5 mm) can either be fed into the vibrating sieve or directly into the LIBS module. The vibrating sieve separates the material into two particle size fractions. The coarse fraction (+1 to -5 mm) can be stored intermittently or conveyed to the LIBS module via screw feeder. The fine fraction (0 to -1 mm) can either be stored, fed into the LIBS module, or directed to the multi-chamber unit.
- Multi-chamber separator: The fine material <1 mm is further transported to a direct sorting unit designed to further classify the material into a fine and a coarse fraction. The coarse fraction (+0.2 mm to -1 mm) from the direct sorting unit is collected in a storage container. The emerging fine fraction (0 to -0.2 mm) is transported pneumatically to a cyclone and collected in a storage container. The air outlet from the cyclone is directed through a filter to prevent loss of fine particles.
- Cyclone unit: In the cyclone, the material is further classified. The lower output (0 to -0.2 mm) can either be stored intermittently or sent to the LIBS module. The upper fine dust output is conveyed directly to the filter unit.
- LIBS classification and sorting: It must be ensured, by controlling the 2-way valves, that only one of the stated pathways, therefore one defined grain size fraction is fed into the LIBS module at any given time, while all others are directed to the corresponding intermittent storage. 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 in the multi-chamber separator and proceed directly to the LIBS module for online analysis. Based on the measurement data obtained, a mechanical flap is installed to divert the material into two separate storage units, allowing enrichment or depletion of desired components in the final material stream, allowing for a maximized output of valuable product concentrates.

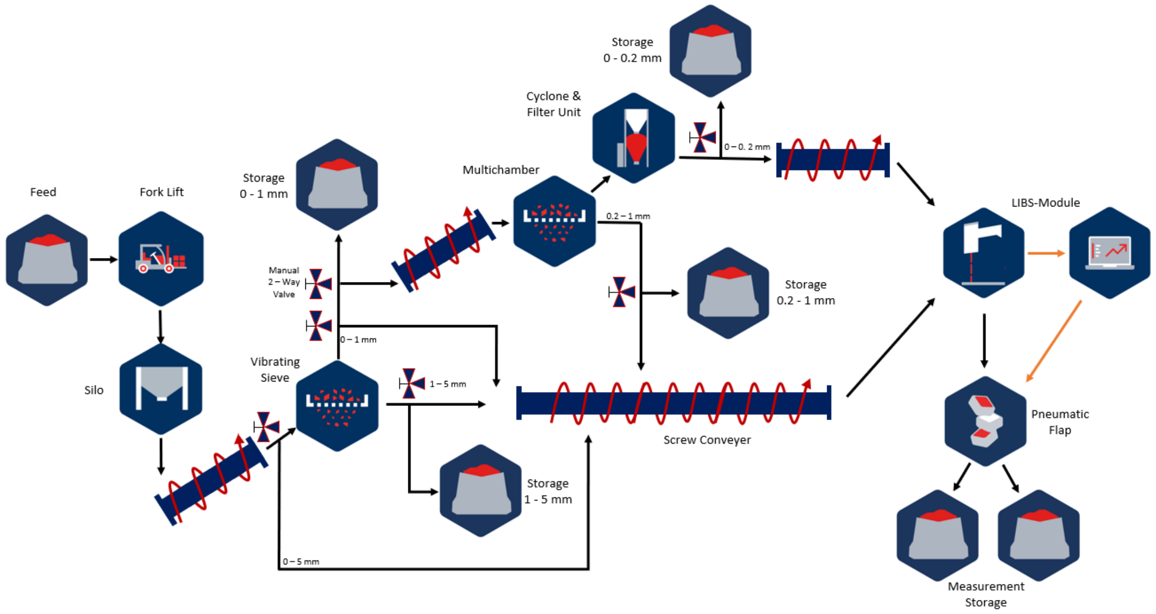


Figure 5: Process flow of Demonstrator B.

<u>Possible Processing of collectable Reject Fraction</u>

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

Based on the feed 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 (in future implementations) – 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 preceding 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 the 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 got 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 or other handling within the Demonstrator.

Although this material is directed to the preliminary 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 WP 9.

As mentioned above, another aspect to be considered for the reject fraction before reintroducing it to either Demonstrator A or B, is the imperfect classifying of the sieves during material preparation (fines stuck on coarse grains) and within the demonstrators as well as generation of fines during material handling in bunkers and conveyer belt transfer points due to abrasion. Consequently, there is a possibility that the feed material for Demonstrator A (+5 mm to -120 mm) may contain additional inter-process generated fines. This necessitates subjecting all collected rejects intended for reprocessing within the presented flowsheet, regardless of the feed material fraction, to an additional sieving step as preparation for reprocessing. This ensures the separation of the material into feedstock suitable for Demonstrator A and B, depending on particle size requirements.

4. Future implementations and adaptations

Data based improvement iterations

The finalized flowsheet gives an overall qualitative view of the interlinked singular steps but does not deliver information on their quantitative effect on the operation. As the understanding of the effects of the singular parts is crucial for continuous improvement efforts extending beyond the project lifetime of ReSoURCE, a spreadsheet model was created, that can be filled with future collected data to gain insights and understanding in the interlinked operations of the demonstrators. As of now, the model is based on necessary assumptions due to the demonstrators being limited in their ability to generate data that can be directly compared to other state-of-the-art processing approaches with higher operational maturity. The final state of the spreadsheet model is visible in Figure 6. Among the assumptions are e.g. strict mass-based flows, not yet linked to varying densities, as well as constant material humidity, process stability, flowability or transportability, no changing behaviour along the flow sheet and omitted seasonal influences, which might impact operational performance. With future iterations and improvements made on the demonstrators and subsequent reduction of these assumptions, the model can be refined to infer practical learnings with a higher degree of confidence.

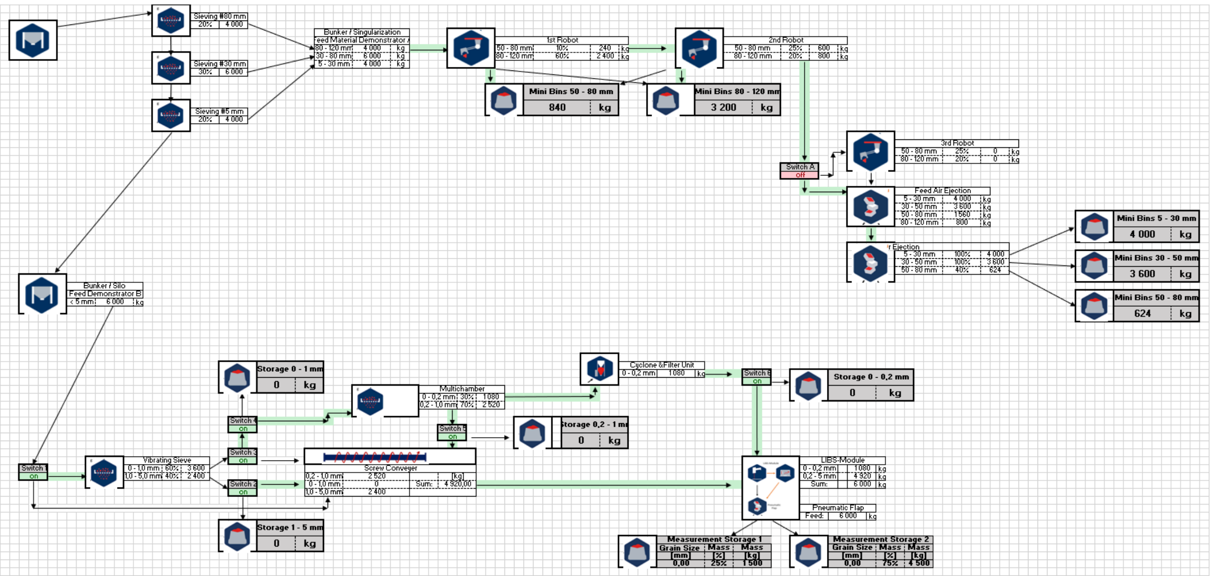


Figure 6: Visualization of interlinked final flowsheet model.

Possible cascade operation

In future, trials within a cascade operation of the demonstrators are planned after the project, so that reject material can directly be brought back in the demonstrators as input fractions. Such trials assign empirically defined roles called “Rougher”, “Scavenger” and “Cleaner” to demonstrator units. These operations have the goal to extract as much valuable products as possible, while simultaneously reducing processing losses. If these cascade trials show valuable results the effective amount of recycled refractory material can increase significantly.

Interlinking Demonstrator A and B

The interconnection of the two demonstrators can be approached with different views in terms of scalability. Considering any bottleneck in throughput to be identified within Demonstrator B, it is assumed to be the basis of a formulaic approach. As already stated in Section 3, processing and reprocessing of mass flows from Demonstrator A in Demonstrator B is sensible to reduce losses of valuable products in the fines. However, as already stated, the interconnection between the demonstrators has to have a classification step in between to ensure the correct mass flows going to the correct demonstrator. The inputs for Demonstrator B are on the one hand in the grain size range 0 to -5 mm from pre-processing, and parts of the fall-throughs and filters/dedusting units. As the fall-throughs are usually coarser, it is assumed that approximately 2.5 % of total mass flow from fall-throughs can be reprocessed within Demonstrator B. Therefore, the formula for an estimated generalized utilization is as follows:

$$\frac{Preprocessing\ mass\ flow + (fallthroughs\ x\ 0.025) + filter\ mass\ flows}{Total\ throughput\ of\ Demonstrator\ B} \approx 0.95$$

The closer the result to the 0.95 or 95% as set goal for total utilization, the better the design fit for a specific use case of Demonstrator B. For Demonstrator A, an analogous approach can be used, while this generalized view may not be sufficient to accurately estimate a utilization for Demonstrator A, as the throughput should be significantly higher than for Demonstrator B due to the input steam grain size distribution.

As the classification step in between is necessary, the interlinking can be seen as discontinuous, as the above stated material flows cannot be connected into one input flow for Demonstrator B without significant material handling in between.

Use cases for the operation of the robot ejectors

To illustrate the different behaviours on the ejection units of Demonstrator A, two different input grain size distributions as stated in Table 4 have been investigated. The goal was to get an insight into the expectable output grain size distribution while reducing the number of defined fractions to 2.

Table 4: Exemplary grain size distribution for Demonstrator A

Particle size class [mm]	Mass fraction 1 [%]	Mass fraction 2 [%]
5 – 30	50	0
30 – 80	50	60
80 – 120	0	40
Sum	100	100

As is visualized in Figure 7, significant differences can be seen between the two cases. Mass fraction 1, being the case without coarse grains in the range of +80 to -120 mm shows a grain size distribution with an associated fall-through of approximately 7.5 % of total mass flow. Mass fraction 2 on the other hand is the edge case without fine grains in the range of +5 to -30 mm and has an associated fall-through of approximately 17 %, which is significantly higher due to the two robot ejection units being not effective enough to eject all incoming suitable grains. Another aspect to consider is the higher associated mass with a coarser grain size, also impacting the higher rate of fall-through. In general, it can be stated that a very coarse input stream would necessitate a 3rd robot ejection unit to show similar separation performance relative to usual grain size distributions.

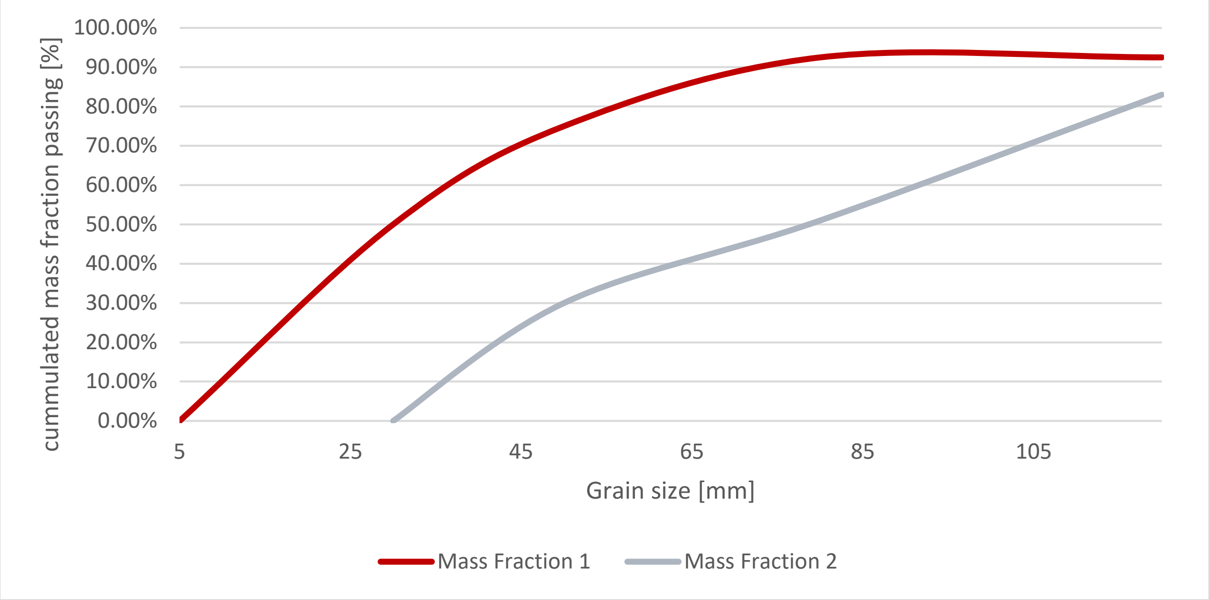


Figure 7: Hypothetically resulting grain size distributions after processing in Demonstrator A

Expansion of Demonstrator A with a 3rd robot

After the project lifetime of ReSoURCE, it is planned to install a 3rd sorting robot in Demonstrator A to handle a higher mass flow. For this part, a model was created to interlink the flow sheet in a spreadsheet calculation-based form. As assumed input flow we take the exemplary grain size distribution for SCL from Table 1. An expected distribution of the particle sizes handled by the different ejection devices with a 3rd sorting robot can be seen in Table 5.

Table 5: Estimated distribution of the particle sizes handled by the different ejection devices with a 3rd sorting robot

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

As most effective case, the 3rd robot should be assumed to be identical in operation to the 2nd robot. This will allow a more selective sorting in the particle size range with a higher number of expected ejections as well as the assumption of a limit state of estimated ejections in the range +50 to -80 mm within the air ejection unit of 10 %. These 10 % are chosen as those bigger grain sizes, which end up in a fall-through bin, cannot completely be avoided. Furthermore, bigger particles have a bigger influence on the overall mass flow. As secondary goal to a more selective sorting, protection of the installed equipment by avoidance of higher fall-through as best as possible is desired. By keeping everything within the model calculation constant the amount of sortable particles rises significantly by up to approximately 11%, as can be seen in Figure 8.

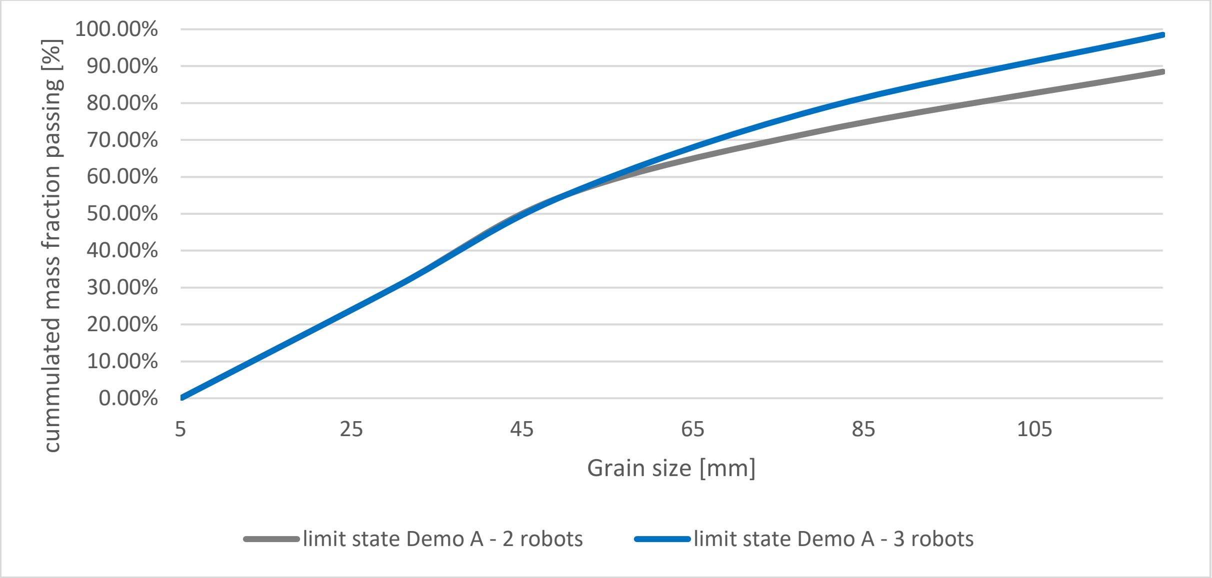


Figure 8: Exemplary grain size distribution after modelling of Demonstrator A with 2 or 3 robots.

By utilization of the model shown in Figure 9 it was possible to estimate the overall effect of the addition of a 3rd robot. Based on the result the integration would allow for a higher recovery of coarse particles while reducing the amount of fall-through, and therefore particles which may need to be reprocessed. Not based on the model result, but on general insights from empirical operation of mineral beneficiation equipment, it can also be stated that an integration would significantly prolong the inherent equipment lifetime of the air ejection unit, while also allowing for a smoother operation due to a narrower operational grain size range. These insights can be seen as inferred by the model, as calculations based on a higher percentage of estimated ejections in the range +50 to -80 mm than 10% show lower gains at the amounts of sortable particles.

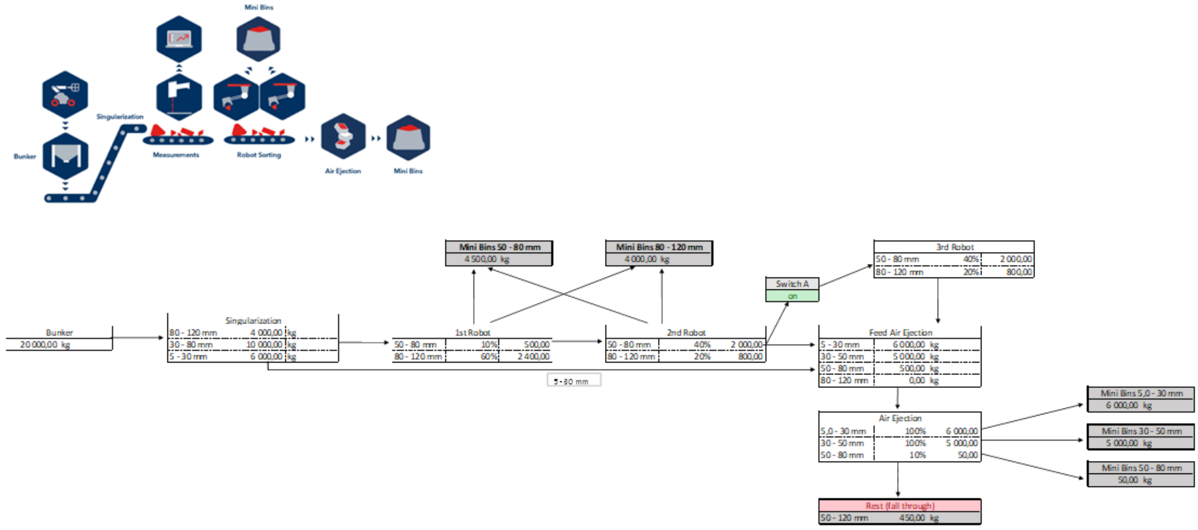


Figure 9: Underlying model assumption for Figure 6.

5. Conclusion

Throughout the project lifetime of ReSoURCE, the handling and sorting of spent refractories from two refractory breakout material groups (Steel Casting Ladle and Cement Rotary Kiln) has been divided into two grain size dependent pathways for their processing, represented by the dedicated Demonstrator A (RAPTOR) for coarse grain sizes and Demonstrator B (PHOENICS) for the fine fraction. This dual approach targeted for each grain size fraction allows for optimal processing of the whole input grain size distribution into valuable recycled products, allowing for a maximized valorisation of the initial feedstock.

Demonstrator A, designed as containerized processing unit within standard freight containers, allows the optimal processing of coarse grain sizes of refractory breakout. Advantages of the produced solution are reduced complexity within the overall recycling approach for spent refractory sources, as the Demonstrator features all necessary functionalities to recycle the feedstock within one unit. Therefore, transporting it directly to the source minimizes necessary material logistics, significantly reducing CO_2e emissions. The Demonstrator features advanced sensors (LIBS, HSI, 3D) and advanced ejection units (robots, tailored air ejection), which deliver a precise sorting result.

Demonstrator B, also designed as containerized processing unit, is a tailored solution for the processing of fine fractions, as the assessment of singularized grains analogous to Demonstrator A is not possible. The Demonstrator offers a wide range of flexibility in between the processing steps, allowing for a smooth operation while also maximizing the valorisation of the input feedstock. This Demonstrator also utilizes advanced sensors (LIBS), but contrary to Demonstrator A, relies on a developed multi-chamber separator unit which mitigates the problem of a missing singularization of the process feed, allowing for a precise classification of fine fractions within the Demonstrator.

The final flowsheet design of the refractory recycling plant developed in the ReSoURCE project represents a critical advancement toward achieving a circular economy in the refractory industry. It outlines a validated, efficient process chain - from initial comminution and sorting to material separation and recovery - based on real mass flows and operational data from the Demonstrators A and B.