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AI-powered Robotic Material Recovery in a Box

RECLAIM

D5.2: Preliminary assessment of prMRF performance

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List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
AI-ILC	Artificial Intelligence-based Identification, Localization and Categorization
DoA	Description of the Action
RDG	Recycling Data Game
prMRF	portable, robotic Material Recovery Facilities
RoReWo	Robotic Recycling Workers
DoF	Degrees of Freedom
HSI	Hyperspectral Imaging
PET	Polyethylene terephthalate
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
PP	Polypropylene
PS	Polystyrene
ALU	Aluminium

Executive Summary

The RECLAIM project brings together cutting-edge research in robotics and gripper technologies, artificial intelligence, computer vision, hyperspectral imaging, and established waste management practices to develop a portable robotic Material Recovery Facility (prMRF) designed to significantly improve local-scale waste sorting and material recovery. Key to achieving this objective is the early integration of all involved technologies and testing activities that facilitate guided improvements on the composite system.

Work Package 5 focuses on the integration of advanced enabling technologies provided by RECLAIM partners and their deployment and joint operation within the prMRRF container box.

The present Deliverable aims to provide a first assessment of the prMRF analyzing the individual and collective performance of the enabling technologies in material recovery tasks.

This deliverable includes six (6) sections. After a brief introduction in section 1, section 2 summarizes the structure of the experiments conducted to assess the performance of the individual enabling technologies both independently and collectively.

Then, section 3 reports on the evaluation of the mechanical equipment installed inside the prMRF which is intended to support the spread and transport of recyclables.

The next section discusses experiments aiming to systematically assess different gripping technologies in waste picking tasks. This analysis aims to offer recommendations for optimizing their usage and enhancing their effectiveness within the prMRF.

Section 5 compares the three different RoReWo configurations considered in RECLAIM assessing their speed and picking success in material recovery tasks sharing similar characteristics.

The subsequent section reports on the performance of the RGB image processing module, focusing on its ability to detect recyclable objects and classify them based on their material type. It further discusses the accuracy of the module in distinguishing between different categories of recyclables and highlights challenges encountered during the categorization process that require further exploration.

Section 7 summarizes the current state of HSI processing and discusses the expected integration of HSI outputs in the prMRF procedures, early in the second phase of the project.

The next section evaluates the performance of the first integrated version of the prMRF under a realistic setting, where it is tasked with sorting a mixed stream comprising five distinct materials. The results from this assessment confirm the effectiveness of the methodologies implemented in RECLAIM and highlight areas for promising future developments.

The final section offers conclusions and connects the work completed in WP5 to ongoing efforts in other Work Packages (WPs) within the RECLAIM project.

1 Introduction

In the first months of the RECLAIM project, we have exploited the extensive expertise of ROBENSO and HERRCO in applied waste management solutions, for choosing, purchasing, implementing and integrating the hardware and software components that are necessary for the operation of the portable, robotic Material Recovery Facility (prMRF) targeted in the project. The relevant components regard the container-box and the mechanical equipment that supports waste transfer and treatment, the computer vision module and the hyperspectral imaging module that together enable the identification, localization and categorization of recyclables, the newly introduced Robotic Recycling Workers and the grippers to be used for picking and sorting different materials. The first phase of RECLAIM completed with the early integration of the relevant components in order to promptly reveal/mitigate conflicts in the waste processing chain. The present Deliverable aims to provide a first assessment of the prMRF analyzing the individual and collective performance of the enabling technologies in material recovery tasks.

During the initial phase of the RECLAIM project, we have exploited the substantial expertise of the consortium in delivering practical waste management solutions for selecting, purchasing, implementing, and integrating the essential hardware and software components needed for the operation of the targeted portable, robotic Material Recovery Facility (prMRF). These components include the container-box, the mechanical systems that facilitate waste transfer and treatment, and the advanced technology modules such as computer vision and hyperspectral imaging, which together aim to provide advanced capabilities for the identification, localization, and categorization of recyclable materials. Additionally, the integration of newly developed Robotic Recycling Workers (RoReWos) and the specialized grippers designed for picking and sorting various materials was prioritized. This first phase concluded with an early integration of these components, into the first version of the prMRF.

The current Deliverable aims to present a preliminary evaluation of the prMRF by analyzing both the individual and combined performance of the enabling technologies in executing material recovery tasks, in order to facilitate the timely identification and resolution of potential conflicts within the waste processing chain.

1.1 Intended readership

The present report is a public (PU) document. Its readership is considered to be the European Commission, the RECLAIM Project Officer, the partners involved in the RECLAIM Consortium, beneficiaries of other European funded projects, and the general public.

1.2 Relationship with other RECLAIM deliverables

This deliverable is related to the deployment of all the technologies developed in RECLAIM. In the coming months of the project this deliverable will serve as a reference point for RECLAIM partners that need to coordinate activities in order to achieve efficient operation of the components they develop inside the prMRF.

The achievements summarized in the current deliverable are directly or indirectly related to multiple past and future deliverables which are enlisted below.

Table 1. Other RECLAIM deliverables related to Deliverable 5.1.

Del. No	**Deliverable Name**	**WP**	**Month**
2.1	prMRF and RDG requirements and systems specification	WP 2	M6
5.1	Early prMRF development based on available enabling technologies	WP 5	M9
3.1	Material recognition based on RGB and Hyperspectral imaging	WP 3	M18
4.1	Gripping mechanisms and RoReWo units for material recovery	WP 4	M18
6.1	Waste Data for material recognition and Recycling Data Game	WP 6	M18
6.2	Algorithms and pipelines for Recycling Data Games	WP 6	M18 / M30
6.3	Assessment of the Recycling Data Game	WP 6	M18 / M36
3.2	prMRF operation monitoring and repeating advancement	WP 3	M30
4.2	Multi-robot / multi-gripper RoReWo-Team configuration	WP 4	M30
5.3	Final assessment of prMRF and sustainability plan	WP 5	M36
1.3	Final Project Report	WP 1	M36

2 Structure of the experiments evaluating the prMRF and enabling components

This section provides the structure of the experiments conducted in order to shed light on the performance of the core components supporting the operation of the prMRF. Following the prMRF architecture, we identify five key components that require evaluation independently, assuming optimal performance from adjacent or cooperating modules. Moreover, assessing the synergetic operation of these components is essential to obtain an overall understanding of the prMRF's total effectiveness.

More specifically, the components that are evaluated are listed below:

- The mechanical equipment installed in the RECLAIM container-box. This regards mainly the conveyor belts and the magnet that are installed in the prMRF, which need to operate for long hours effectively transporting materials and feeding robotic sorters.
- The grippers that have been selected as most appropriate for waste sorting tasks. This regards the efficiency of the grippers on picking up recyclables and determining if some grippers are more effective for specific types of materials.
- The different architectures of Robotic Recycling Workers (RoReWos) that operate above the conveyor belt, to implement the physical sorting of the transported recyclables. This regards the analysis of the different RoReWo architectures considered in RECLAIM, linking the number of picks each architecture achieves per minute associated with success rates.
- The computer vision component of the AI-ILC module that processes RGB images showing recyclables transported on the conveyor belt. The evaluation regards identifying recyclables and matching them to one of the material types considered in RECLAIM.
- The HSI component of the AI-ILC module that process hyperspectral images showing recyclables transported on the conveyor belt. This regards the ability to accurately categorize objects into their proper material types.
- The first version of the composite prMRF in terms of physically sorting recyclables into seven different material-specific bins.

3 Evaluation of the mechanical equipment inside the prMRF

Before examining the autonomous and intelligent sorting of recyclables inside the prMRF, it is necessary to assess the performance of the supporting equipment that spreads and transfers recyclables, facilitating the categorization and picking of waste.

To this end we create a stream of mixed recyclable waste that is used in a material looping experiment where the objects are placed on the inclined belt to then transfer to the vibrator, the forward moving belt, the return slide, the backward moving belt and again the inclined belt to close the loop. The objects were circulating for 30 minutes which corresponds roughly to 15 cycles.

During the operation we inspected the movement of the recyclables. In short, we have overall observed that the installed equipment completes the targeted task and recyclables were circulating as planned to enable prMRF demonstration and extensive, long-lasting experimentation.

What is of particular interest in RECLAIM is how waste is distributed on the forward-moving belt where pickup is actually executed. Despite using a vibrator to enhance spreading, it has been noted that objects being very flat and light tend to accumulate on the left side of the belt. This is especially true for PP/PS materials and, to some extent, for flatten Tetrapack packages. Recognizing this pattern could be crucial for optimizing the placement of collection bins on the two sides of the belt. By strategically locating material types on the left or right side, we could minimize the distance the RoReWos have to travel, thereby reducing the time required for each waste sorting cycle.

Additionally, we noticed that at belt crossings, where items are transferred from one conveyor to the next, there were instances of thin items getting wedged between different belts. Such incidents can result in the first wedged object causing a larger group of objects to be temporarily blocked. Although the wedging of thin objects between belts has not currently significantly disrupted prMRF functions, it is an issue that requires thorough investigation in future iterations of prMRF, particularly if commercialization is considered.

4 Evaluation of different grippers on waste picking

A framework has been developed for the evaluation of the performances and relative importance of distinct gripper systems in the specific application of waste sorting with the aim of guiding the optimal implementation of these systems within the prMRF. This framework is further elaborated in the article titled: "Sorting of Packaging Waste: a Framework to link Gripper Technologies and Waste Classes", which is accepted for publication in the CIRP LifeCycle Engineering conference 2024 to be held in Turin, Italy.

The current study is structured according to this framework aiming to provide an informed strategy for allocating different materials or recyclables within a waste stream to the available grippers considered in RECLAIM. By sampling the targeted "Blue-bin" stream the relative presence of different materials of products (classes) is statistically defined by measuring the total weight of the different material types that are encountered in the sample, as shown in Table 1.

Table 1. Material composition of the RECLAIM waste stream.

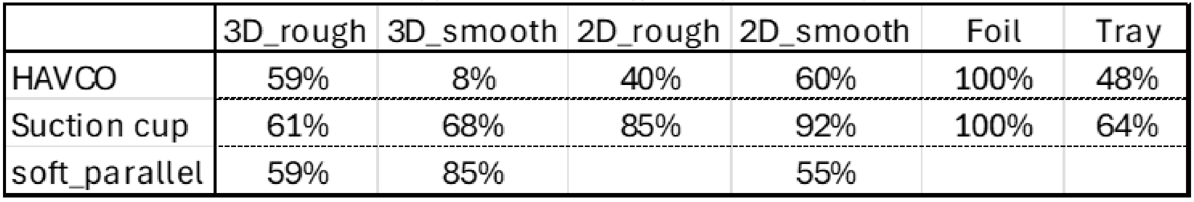
Material	Mass (t)	Mass share (%)	Avg. item weight (g/item)
TETRAPACK	74	4%	39
PET	597	34%	33
PE - bottles	82	5%	104
PE - film	431	24%	48
Multilayer-film	23	1%	
PP	211	12%	40
PS	30	2%	40
AL	96	5%	15
FE	236	13%	87
SUM	**1.781**	**100%**	**50.75**

Each of the classes representing mass consists of objects of different product shapes. While collection bins are specified according to the material or the type of the recyclables, the ability to grasp a product is mainly defined by the shape and weight of the product. However, in waste sorting applications products have a major variation in shape while their weight tends to be relatively consistent since post-consumer waste is mostly empty. In other words, the material type alone cannot serve as a distinguishing criterion due to the inhomogeneity of the product stream. Hence, objects are also to be described based on the volume they take and the surface structure they have.

Therefore, the present study aims to explore object gripping considering not only the material type but also the shape of waste. Along this line six classes based on the different shapes encountered in the waste stream are proposed to attempt to efficiently connect grippers to the products: 3D – rough, 3D – smooth, 2D – rough, 2D – smooth, films and trays.

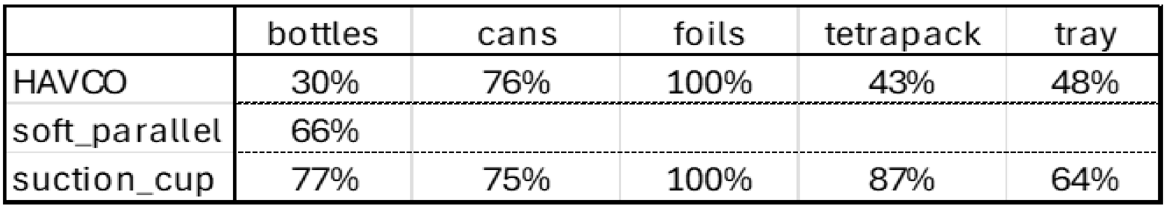
Today, the distribution of the different materials over the different products to the different product shapes is still unknown. Therefore, this will be defined in future work by analysis of images collected at the prMRF, for example to define that 40% of PET bottles are 3D-rough and 60% are 2D-rough. What has already been investigated at the moment of reporting is the grasp efficiency of specific gripper types on these six specific product shapes. For this, empirical experiments are performed with the prMRF system at Heraklion, Crete. For these experiments 3 distinct gripping principles are installed: suction cup grippers on the 1.5 DOF robots, a parallel gripper on the 3.0 DOF robot and a HAVCO gripper on a 1.5 DOF robot, as described in Deliverable 4.1. In total, more than 1000 objects of different material classes and shapes were sorted by these 3 grippers. Through analysis of the videos captured during the experiments and combining the video analysis with the logging data of the vision system and the robot controller. The gripper performance against the different shapes and the different material types considered in RECLAIM is defined, as shown in Table 2 and 3.

Table 2. Gripper success on different product shapes.



	3D_rough	3D_smooth	2D_rough	2D_smooth	Foil	Tray
HAVCO	59%	8%	40%	60%	100%	48%
Suction cup	61%	68%	85%	92%	100%	64%
soft_parallel	59%	85%		55%		

Table 3. Gripper success on different product types.

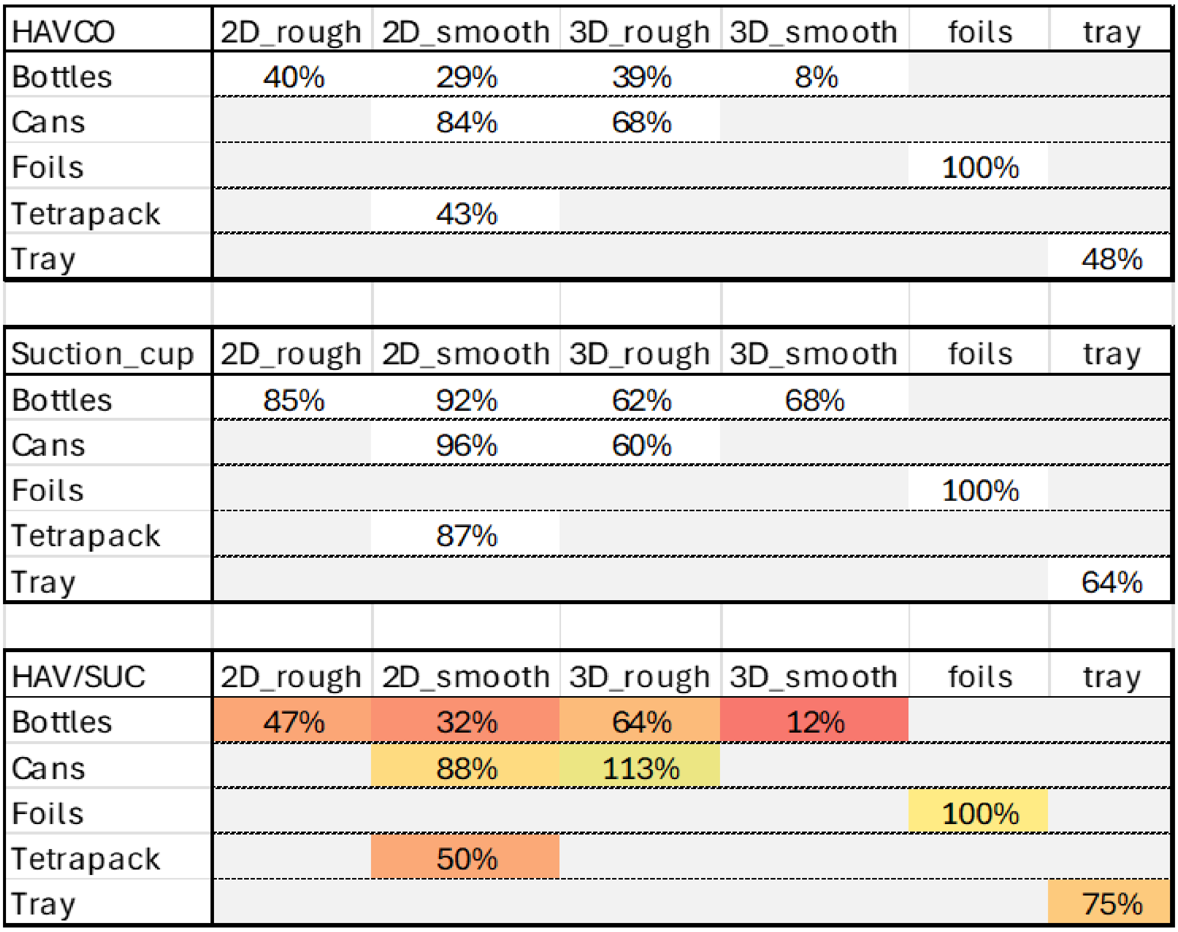


	bottles	cans	foils	tetrapack	tray
HAVCO	30%	76%	100%	43%	48%
soft_parallel	66%				
suction_cup	77%	75%	100%	87%	64%

Both tables show that gripper performances vary heavily between the different shape classes and product types. By classifying the different waste materials that enter the pr-MRF the gripper with the highest probability for successful picking the specific shape and waste category can be selected ensuring the highest overall efficiency of the prMRF. During the analysis of the data some video material for the assessment of the success of the picks appeared to be missing. For this reason, additional testing is planned to complete the tables for the soft-parallel gripper.

In Table 4 the success rates of both the product shape and type are shown for the HAVCO and suction cup, which allows to define decision rules for the assignment of grippers. Additionally, a comparison is made between the HAVCO and suction cup gripper, showing the success ratio for the HAVCO and the suction cup gripper, as well as their relative success. Various cells of the tables are coloured gray indicating the absence of the specific shape for the considered product types.

Table 4. The gripper success on different product types and materials and the performance comparison between the HAVCO and suction cup gripper.



HAVCO	2D_rough	2D_smooth	3D_rough	3D_smooth	foils	tray
Bottles	40%	29%	39%	8%		
Cans		84%	68%			
Foils					100%	
Tetrapack		43%				
Tray						48%

Suction_cup	2D_rough	2D_smooth	3D_rough	3D_smooth	foils	tray
Bottles	85%	92%	62%	68%		
Cans		96%	60%			
Foils					100%	
Tetrapack		87%				
Tray						64%

HAV/SUC	2D_rough	2D_smooth	3D_rough	3D_smooth	foils	tray
Bottles	47%	32%	64%	12%		
Cans		88%	113%			
Foils					100%	
Tetrapack		50%				
Tray						75%

As shown in Table 5, the suction cup gripper outperforms the HAVCO gripper on the picking of 2D_smooth and 3D_smooth bottles. The HAVCO has comparable or slightly better performance on 3D_rough cans and foils and performs slightly worse on 2D_smooth cans and trays. Hence, when a HAVCO gripper is installed alongside suction cup grippers, the HAVCO gripper can serve as an alternative for suction cup grippers when the suction cup grippers are overloaded. In this scenario the HAVCO gripper could also pick Tetrapacks, 2D_rough bottles and 3D_rough bottles with a penalty of around 50% efficiency. The evaluation on the picking success of both grippers, on cans for example, show that selecting the gripper based on only the product type might be insufficient since the results indicate that picking the flattened cans (2D smooth) with the suction cup and the crushed cans (3D_rough) with the HAVCO gripper might lead to higher efficiency. Therefore, further analysis will also look into the use of outer dimensions as an evaluation criterion, which can easily be derived from the object masks that are saved in the logging by the computer vision system during all performed tests. Hence, gripper success in function of both the object material class and geometry will be further analyzed, to define optimal criteria for task assignment starting from the product images considering the gripper capabilities and limitations. To enhance these analyses, additional experiments are recommended in which a larger number and broader variety of object sizes are used. Building on the experiences and method developed for assessing gripping success, the automatic logging of the gripper success from the vacuum sensors and/or from optical sensors in the output bins is recommended to ease larger scale data collection.

In the remainder of the project, the objective is to also define the total throughput, as well as the expected loss during grasping. For this, the performance of the graspIng results will be combined with the planned composition analysis. Next, different scenarios will be evaluated in which products with different material classes and geometries will be targeted for grasping by distinct sets of grippers. For this, the presented framework will be used to select the right gripper combinations. With the framework developed for evaluation of gripper performances in function of the object shapes and material categories, this will allow us to produce diagrams as shown in Figure 1 and 2. In the first instance (Figure 1), the objective is to define rules to assign every object to one of the gripper mechanisms based on the experimentally defined gripper efficiencies in function of shape, size and waste category. In the second instance (figure 2) the objective is to evaluate the gripping success considering the number of grippers of each type integrated in the prMRF and their picking speed. However, to correctly produce these graphs, aside from the composition analysis in function of geometries/shapes, task allocation among the different robots is to be considered. For this purpose a discrete event simulation environment is under development to test distinct task allocation algorithms and robot/gripper setups under varying waste throughputs.

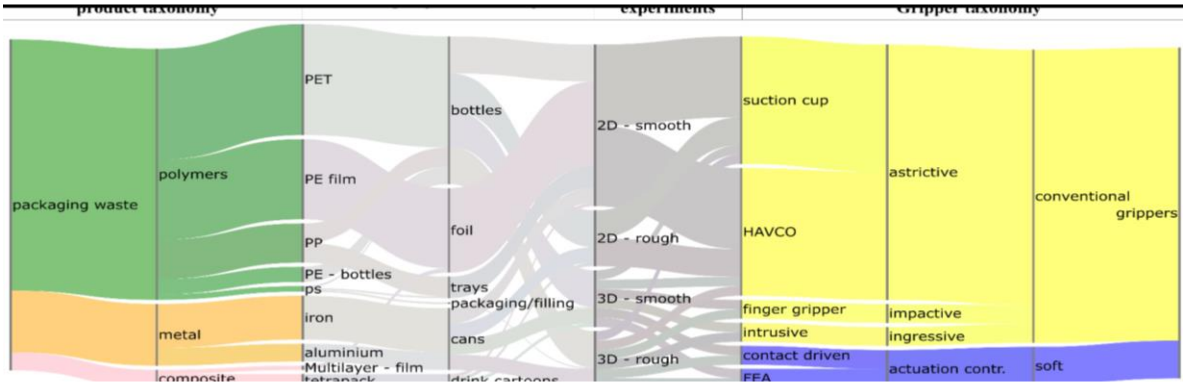


Figure 1. Sankey diagram visualizing the proposed method to link gripper technologies and waste classes.

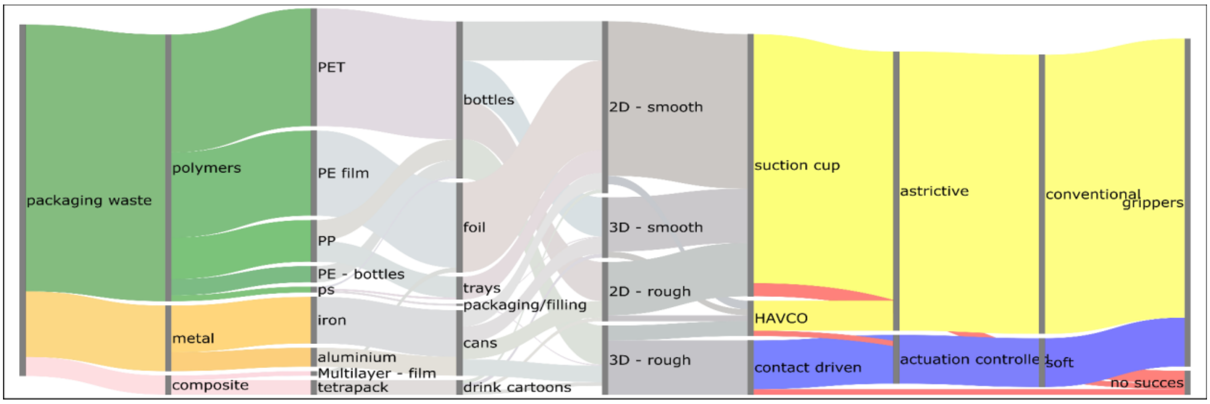
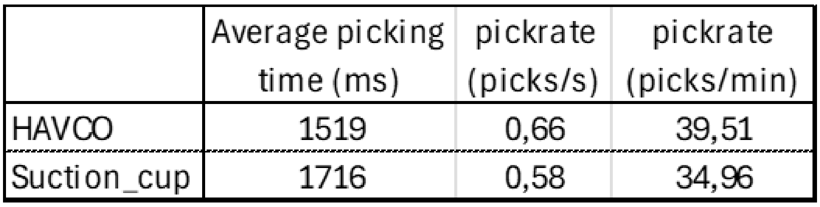


Figure 2. Performance evaluation of selected grippers.

For optimal task planning and assessment of the prMRF in the simulation environment the actual grasping speed is also important to take into account. Therefore, the times for gripping are logged by the robot controller for all grasps performed for actuation of the linear axis, the vertical axis, termination of upward movement and the drop-off of the object. Based on these experiments the total time can be derived in function of the X position of the object, as well as the total average picking times, as shown in Table 5.

Table 5: Pick rates for the evaluated grippers based on the average picking time.



	Average picking time (ms)	pickrate (picks/s)	pickrate (picks/min)
HAVCO	1519	0,66	39,51
Suction_cup	1716	0,58	34,96

Important to consider is that all gripping experiments were performed with the same robot motion profile, leaving substantial potential for optimisation of the motion profile and, hence, also the gripping time for the HAVCO gripper. However, in lab tests a total picking time of <0,35 seconds per pick or >170 picks per minute was demonstrated when using an industrial Staubli Scara robot. Therefore, the values reported here are to be considered as a lower bound. For the HAVCO, the majority of the objects to be assigned will be sucked up, allowing the HAVCO to be used in a pick-pick-pick scenario instead of a pick-drop-pick scenario, eliminating part of the robotic movement. Therefore, additional tests are to be performed to correctly evaluate the gripping times, as for the HAVCO 55 picks per minute is based on the performed experiments assumed to be possible.

5 Evaluation of the different RoReWo architectures

The implementation of various types of Robotic Recycling Workers (RoReWos) with varying degrees of freedom within the RECLAIM project addresses a crucial need to enhance efficiency and flexibility in recycling operations, particularly within the prMRF.

As detailed in Deliverable 4.1, RECLAIM has introduced three cartesian RoReWos, each equipped with different degrees of freedom: 1.5, 2.5, and 3.0. These variations in mobility and flexibility significantly influence the robots' capability to reach, pick and sort recyclable materials, but at the same time affects implementation costs.

This report compiles a series of experiments designed to evaluate the effectiveness of each RoReWo configuration in material sorting tasks. For uniformity in testing, each robot is fitted with the same type of suction cup gripper and tasked with handling the same set of material. The focus of the evaluation is on PET bottles, which are a major component of recyclables in Greece, also considered among the most valuable materials in Material Recovery Facilities across Europe.

Dataset Description: In an effort to ensure a realistic representation of the materials found in typical blue-bin recycling contents, PET bottles of different sizes and conditions were sourced from the local Material Recovery Facility (MRF) managed by HERRCO. This selection was made to closely mimic the variety of items one might find in a real-world setting. For the purpose of these experiments, two common sizes of PET bottles were chosen: 500ml and 1.5L, making up a total of 60 samples. These bottles varied in shape, including standard forms as well as those that have been flattened or crushed, mirroring the diverse states in which bottles are commonly discarded by citizens.

The bottles were manually distributed on the conveyor belt at a slow pace that allowed the RoReWos to adequately approach and pick them up. The results of RoReWo performance are summarized in Table 6.

Table 6 The results of the evaluation of suction cups on different robots

RoReWo DoFs	Picks / Minute	Avg Pick Time (s)	Attempts	Sorted	Success Rate (%)	Implementation Cost
1.5	35	1.71	56	47	83.9	8 K €
2.5	32	1.93	58	50	86.2	15 K €
3.0	29	2.1	56	51	91.0	22 K €

Discussion. In the 1.5DoF RoReWo configuration, characterized by a fully controlled movement along a single axis (X), the system demonstrated a high pick rate of 35 picks per minute. This gave also the lower Average Pick Time that represents the average duration of the sorting cycle. The 1.5 DoF RoReWo was unable to reach all objects, thus accomplishing 56 picking attempts out of the 60 possible. The picking success rate was 83.9% which is the lower measured in the current set of experiments. This lower success rate can be attributed to the hard grip resulting from the uncontrollable motion profile of the piston actuator operating at the Z axis. The 1.5DoF RoReWo has particularly low implementation cost due to its simplicity and fewer degrees of freedom, which is approximately 8000 euros. Therefore, it accomplishes a particularly high picks per invested euro rate that is $47/8000 = 5.8 *10^{-3}$

The 2.5DoF configuration, incorporating movement along both X and Y axes, exhibited a slightly lower pick rate of 32 picks per minute, although overall it made more pick trials. This is explained by the fact that the piston moves over a 2D plane rather than a 1D line, thus providing the ability to actively move towards the PET bottles and pick them. The picking success rate was similar to the one accomplished by the 1.5 DoF RoReWo, which is explained by the fact that in both cases the motion at the Z axis is implemented by a piston. Still, the picking success rate was slightly improved reaching 86.2%. This enhancement in success rate is attributed to the system's ability to track targets during the picking process. The addition of the Y-axis, however, contributes to increasing the implementation cost that is now estimated to 15000 euros. Therefore, the corresponding picks per invested euro rate is $50/15000=3*10^{-3}$.

In the 3.0DoF configuration, which offers fully controlled movement along all three axes (X, Y, and Z), the system achieved a pick rate of 29 picks per minute, the lowest among the configurations. The picking attempts were also lower because the 3.0 DoFs result in a relatively heavy configuration that is unable to move fast. However, the current RoReWo configuration demonstrated the highest success rate of 91.0%. This success can be attributed to the controllable motion profile of the Z actuator, allowing for a smoother contact approach during picking. The increased cost of this configuration is associated with the additional degrees of freedom. This configuration is the one with the highest implementation cost that reaches approximately 21000 euros. Therefore, the corresponding picks per invested euro rate is $51/23000=2.2*10^{-3}$.

Overall, the aim of this study is to evaluate the various RoReWo configurations to provide strategic guidance for future prMRF developments. The goal is to identify the optimal waste sorting solution that balances the degrees of freedom with effective gripping capabilities and at the same time ensure that the system can efficiently and quickly pick a wide range of recyclables and material types, thereby optimizing both performance and cost-effectiveness in prMRF waste management.

The results presented above on the comparison of the different RoReWo configurations, which were designed and developed with the aim of applying them to waste management, show that the simpler configuration is lighter and thus can achieve slightly higher sorting speed. On the other hand, it lags slightly in efficiency as more complex solutions have the potential to achieve higher rates of picking success. Therefore, there is no clear criterion that leads to the selection of a single, best RoReWo system. Here we should also take into account that the feeding of the robots was done manually with the aim of keeping them busy throughout the experiments. The RoReWos that had the ability to move in the Y axis managed to move towards almost all targets, while the 1.5 DoF RoReWos failed to adapt to occasionally imperfectly timed manual feeds of recyclables, which resulted in objects that the robot did not attempt to grasp.

However, when considering the costs associated with each RoReWo configuration, the simplest systems emerge as the more sustainable choice. This is because the cost per successful material recovery is substantially lower with simpler configurations. For instance, with the budget required for one 3.0 DoF RoReWo, it is feasible to construct three 1.5 DoF RoReWos, potentially tripling the material recovery capacity. It's important to mention that this cost-effectiveness assumes that all RoReWos are equipped with a suction cup and vacuum gripper. Nevertheless, if the integration of different types of grippers proves advantageous such as the case of HAVCO (refer to the relevant study in the previous section), then RoReWo solutions with more degrees of freedom would have a clear advantage.

The comparative tests will continue in the following months of RECLAIM so that upon the completion of the project there will be a clearly stated proposal regarding the best use of RoReWos inside the MPF in order to optimize the performance of the overall system.

6 Evaluation of waste detection and categorization based on RGB images

As described in Deliverable 3.1, the AI-ILC module is tasked with processing RGB images in order to identify, localize, and categorize recyclables. This module utilizes the Mask R-CNN models that have been trained using both real and synthetic data to carry out the underlying task.

Given that Mask R-CNN infers the area on the image that corresponds to each recyclable object, the evaluation of the models summarized in Deliverable 3.1 focuses on assessing model accuracy at the pixel level. On the one hand, this approach has been useful for the theoretical evaluation of the developed models. On the other hand, the accuracy in specifying the masks of the objects appearing in an image has a minor effect on recyclable recovery. Instead what is of highest interest in waste sorting applications is the percentage of recyclable items that can be identified and correctly categorized as belonging to a certain material type. For this reason, this is also exactly the topic of the study summarized in the present document.

In particular, we performed five experimental sessions considering single-material streams and one more additional experiment considering mixed-material waste streams. In all experiments, the Mask R-CNN model presented in section 3.4 of Deliverable 3.1 has been employed.

All single-material streams consisted of 200 items of either PET or HDPE or Aluminium or PP/PS or Tetrapack. Each stream was manually fed to the vibrator which distributed the objects across the width of the conveyor belt moving forward with a speed of 25 cm/sec. The Mask R-CNN module was slightly adapted to include a counter that tracks all the identified objects and registers all correctly categorized objects of the material type studied at the given experimental session. Table 7 provides a summary of the Mask R-CNN performance for each material type.

Table 7 Success rate for categorization defined in the prMRF

Material Type	Objects Passed	Objects Identified	Success Rate
PET	200	183	91.5%
HDPE	200	177	88.5%
PP/PS	200	162	81.0%
Aluminium	200	187	93.5%
Tetrapack	200	175	87.5%
Average			88.4%

It should be noted that the success rate reported in Table 7 is slightly higher than the success rate reported for the same network in Deliverable 3.1. This difference is because the former evaluates model performance at the object level, whereas the latter assesses it at the pixel level.

To further assess model performance on single-material waste streams, we have also examined the ability of the same Mask R-CNN model to identify and separate recyclables in mixed-material streams. In this experiment we used 100 objects of five different material types to develop a stream of 500 mixed objects. These objects are manually placed on the vibrator which spreads the objects over the conveyor belt width. We followed a pre-specified acquisition rate capturing one image per second. The images are then processed for object identification, localization and categorization. The identified objects are marked on the image and stored locally for manual inspection. The confusion matrix included in Table 8, summarizes the obtained results.

Table 8 Confusion matrix summarizing the multi-class categorization success rate

		ACTUALS					
PREDICTED		**PET**	**HDPE**	**ALU**	**PP/PS**	**TETRAPACK**	**BACKGROUND**
	PET	**85**	**4**	**0**	**3**	**2**	**0**
	HDPE	**2**	**79**	**0**	**11**	**3**	**0**
	ALU	**0**	**5**	**96**	**0**	**6**	**0**
	PP-PS	**2**	**10**	**0**	**76**	**2**	**0**
	TETRAPAK	**4**	**2**	**1**	**2**	**84**	**0**
	BACKGROUND	**7**	**0**	**3**	**8**	**3**	

As can be seen in Table 8, while the categorization and recognition of materials from RGB images is largely successful, there is room for improvement. In particular, the categorization of PP/PS items achieved a lower score, which also indirectly affects the accuracy of HDPE categorization and, hence, requires further enhancement.

This is explained by the fact that the purity of the hand-sorted PP/PS materials which have been used for data collection was rather low. We suspect that HERRCO workers often treat the PP/PS category as the "unknown plastic" category, thus collecting all plastic items in this category that they are not sure where to classify. Inevitably, the low purity of PP/PS materials has clearly affected the training and subsequently the performance of the Mask R-CNN model, as shown in Figure 3.

To resolve the issue with the PP/PS materials, we plan to take advantage of the power of hyperspectral imaging that provides direct information about the material from which the objects are made. Specifically, we will examine all segmented objects one by one and filter the objects used to collect better data for training the models, in which all material types are exactly as registered. Moreover, by using the synthetic data generation approach summarized in Deliverable 3.1 we plan to increase further the PP/PS dataset.

Following the above new training approach for the Mask R-CNN models, we expect to be able to significantly increase the performance of the RGB recyclable categorization module, for all material classes considered in RECLAIM. This will also include PE film objects which are currently not included in our studies. The foreseen models and results will be reported in Deliverable D5.3: Final assessment of prMRF and sustainability plan.

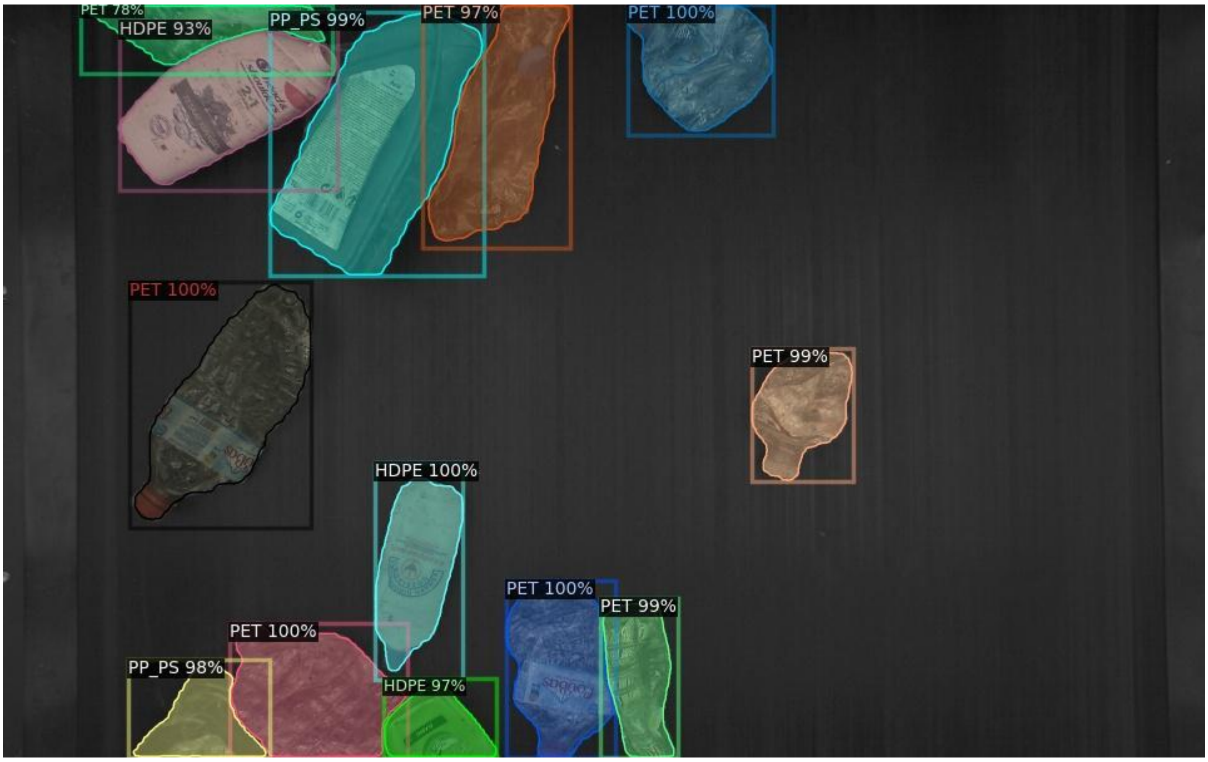


Figure 3. An exemplar image where both objects classified as PP/PS are in fact HDPE objects.

7 Evaluation of HIS-based recyclable categorization

At the time of this report, full integration of the HSI camera into the material categorization and recovery processes at the prMPF has not been achieved. This is primarily due to difficulties encountered in synchronizing the categorization results obtained in the infrared (HSI) and the visible (RGB) domain. These challenges involve aligning and accurately merging the data from both imaging systems to ensure reliable and effective material identification.

Currently, the functionality of the HSI camera is focused on the characterization of individual pixels rather than on the comprehensive characterization of entire objects. This particular aspect has largely been addressed, and we expect to make significant advancements in the near term. In the coming weeks, we are optimistic about achieving more complete and detailed results in the categorization of whole recyclable objects using HSI technology.

Following the above, for the current assessment of the HSI system's performance, we direct reviewers to refer to Deliverable 3.1. The document outlines the efficiency of the system, highlighting its effectiveness in identifying objects made entirely of a single material. The specific success rates for these evaluations are also summarized in Table 9, which provides an early indication of how well the HSI system can distinguish and correctly categorize objects within the recycling stream.

Table 9 Summary of the HSI performance on material categorization

Material Type	Accuracy	Object prediction
PET	92.54%	5/5
HDPE	93.35%	5/5
LDPE	78.02%	4/5
PP	89.71%	4/5
PS	87.37%	4/5
Paper	92.41%	5/5

8 Evaluation of prMRF performance on recyclable recovery and sorting

To assess the effectiveness of the prMRF solution, a comprehensive test was conducted using materials supplied by HERRCO to FORTH to aid in experimentation and system refinement. These materials were manually positioned on the conveyor belt within the prMRF and were progressively intermixed using the facility's looping mechanism.

The five available RoReWos, were prepared to retrieve and sort the materials into 10 different bins. The objective of the experiment was to recover materials of five different types, with each type assigned to the prMRF bins as depicted in picture XXX. The first 1.5 DoF RoReWo aims at the recovery of PET and PP/PS, the second 1.5 DoF RoReWo aims at the recovery of PET and Tetrapack/Paper packages, the third 1.5 DoF RoReWo aims at the recovery of HDPE and Aluminum. Then, the 3.0DoF RoReWo targets Aluminum and HDPE recovery while the last 2.5DoF RoReWo targets Tetrapack/Paper and PP/PS recovery.

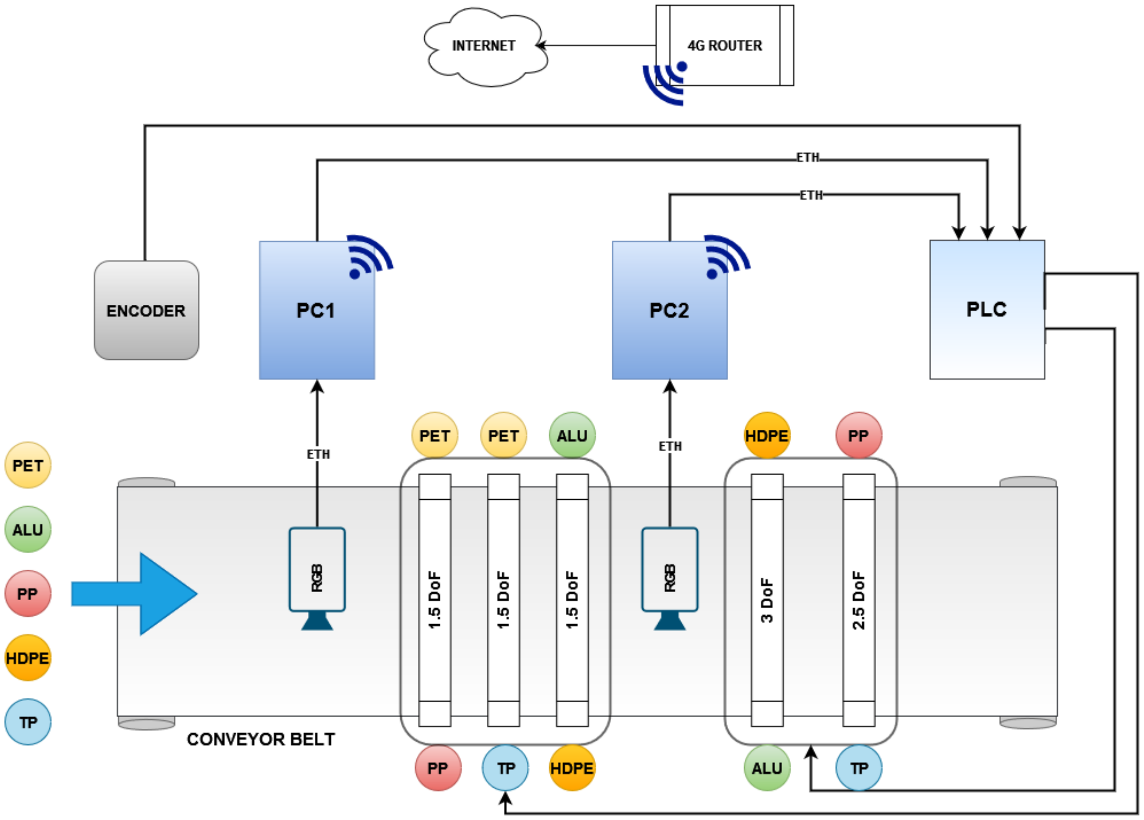


Figure 4. Overview of how collection bins are distributed in material types.

Allocating two different types of materials to each robot is designed to enhance operational efficiency by ensuring that at least one of the target materials is frequently within reach by RoReWos. This strategy increases the likelihood that the robots remain active, continuously contributing to the sorting process and improving the throughput of recyclables. By diversifying the sorting tasks assigned to each robot, we aim to optimize the use of robotic resources, maximizing productivity and minimizing idle time.

When choosing which materials to be sorted by a given RoReWo, priority was given to those that the system identified with a higher degree of confidence. This approach ensured that the physical sorting of objects was more efficient, focusing on materials that could be confidently recognized and correctly categorized, thereby reducing the likelihood of errors and maximizing the effectiveness of the sorting operation.

Given the limited number of recyclables available at FORTH's facilities, the experiment was running for about 5 minutes, which was however enough to give an idea of the efficiency of the first version of the prMRF in full operation. The data collected are presented in Table 10.

Table 10 Summary of the prMRF performance in a five class waste sorting experiment.

Material Type	**Sorted**	**Correct**	**Misclassified**	**Purity**
PET	155	144	11	0.929032
PP/PS	85	68	17	0.8
Aluminum	165	157	8	0.951515
Tetrapack	150	131	19	0.873333
HDPE	90	73	17	0.811111
Total	645			

During the experiment, a total of 645 recyclable objects were successfully sorted, with the robots making 763 attempts to pick materials, resulting in 118 unsuccessful attempts.

When choosing materials for classification, priority was assigned to those identified with greater confidence. This affected the performance of the RoReWo shared between two materials, which tend to work more with that material whose detection achieves the highest success rates.

Nevertheless, as indicated in Table 10, misclassifications were observed in all collection bins, particularly with material types that had lower accuracy in the object recognition and categorization module. This issue has a notable impact on the purity of the recovered materials (see also Fig. 5), highlighting a direction for significant improvements in the upcoming months of the project.

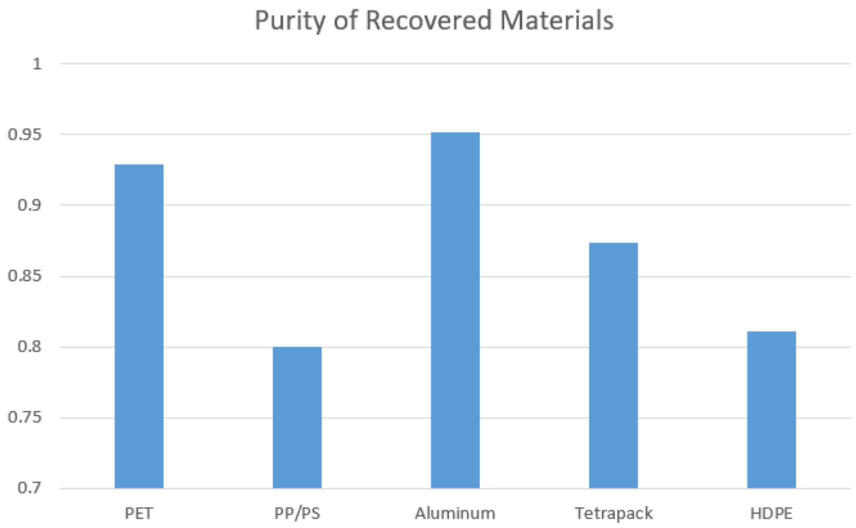


Figure 5. Graphical illustration of the purity achieved for each material type.

9 Conclusions

The present deliverable provides an initial evaluation of all the components deployed at the prMPF, by analyzing their individual and collective performance in recyclable material recovery tasks. The current findings confirm that all core enabling technologies—including mechanical equipment, AI-ILC, grabbers, and RoReWos—operate and collaborate effectively within the prMPF. Additionally, the integration of the HSI camera as part of the decision making process for categorizing recyclables is anticipated soon.

The seamless and effective collaboration among all involved technologies forms a solid foundation for their further enhancements and enables direct monitoring and assessment of their performance in the prMPF, that is their actual working environment.

This will be the primary focus in RECLAIM for the upcoming months. Specifically, we plan to enhance the AI-ILC module by integrating the data from the hyperspectral and RGB image processing units. This integration aims to increase the accuracy of object categorization into material types, thereby significantly boosting the purity rates of the materials recovered by the prMPF. This will be further enhanced by citizen-provided RDG data, which is expected to indicate information-rich images that RECLAIM technical staff will investigate in detail.

Strengthening the performance of all three RoReWo configurations considered in RECLAIM is another priority for the latter half of the project. We aim to particularly focus on boosting their speed and effectiveness in picking and sorting recyclables. Furthermore, we plan to develop a systematic method for assigning different grippers to RoReWos. This will involve creating a simulation environment that enables the analysis of computational "what-if'' scenarios, ultimately improving the overall system performance.

Alongside the preliminary assessment of the prMRF performances, various novel approaches have been developed for experimental validation of the prMRF. Although initial experimental results allow to already assess the performances of a combined vision, robotics and gripping systems, the insights gained to further enhance these empirical experiments in order to obtain more detailed insights in the sorting performances are considered of great value. Hence, the further integration of the distinct technological developments and additional larger scale experiments will also allow to make a proper final assessment of prMRF and sustainability plan to be reported in D5.3.

While the prMPF has not yet reached its optimal performance level, its integrated operation provides a valuable opportunity to amplify the project's impact. Publishing images and videos that showcase the functioning of the prMPF will help communicate the project's objectives and outcomes to both the scientific community and the general public, more effectively. Additionally, the ability to conduct live demonstrations of the prMPF, which is considered the

Minimum Viable Product (MVP) of the project, will enhance engagement with key audiences including the scientific sector, stakeholders in waste management, and potential investors interested in its commercial potential.