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THESEUS

Hub4Circularity

A First of a kind Hub for circularity demonstrator for Attica and peripheral regions

Grant Agreement No 101178059

DELIVERABLE 4.2:

SORTING LINES (TRL5-ready)

Work Package: 4

LEAD BENEFICIARY:

INSTITUTE OF COMMUNICATION AND COMPUTER SYSTEMS (ICCS)

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Document Sheet

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Publishable summary

The **THESEUS project**, funded under Horizon Europe, leads the development of Greece's first **Hub for Circularity (H4C)** in the Attica region, aiming to expand its impact nationally. It promotes Industrial-Urban Symbiosis (I-US) by interconnecting digital, material, and governance innovations to enable the circular utilization of resources across multiple waste streams, including textiles, packaging, construction and demolition waste, energy, and water.

Work Package 4 (**WP4**) focuses on the development of advanced separation and sorting technologies for secondary material streams. Within this context, the project addresses a set of distinct sorting cases, including mixed urban waste, textile waste, plastics recovery from mixed waste, metals separation, and glass sorting. These cases represent different material behaviors, operational environments, and valorization pathways, and therefore require tailored sensing, sorting, handling, and validation approaches.

This deliverable, titled "**D4.2 Sorting Lines (TRL5-ready)**", comprises the first version of the THESEUS sorting line developments. It builds directly on the requirements analysis and conceptual designs reported in **D4.1 "Technologies Requirements"** and presents the first transition from a requirement-driven conceptualization to an implementation-driven validation. The purpose of the deliverable is to document the preliminary development status of the sorting lines and to assess their readiness towards Technology Readiness Level 5 (TRL5), based on module-level, sub-system-level, and preliminary integrated validation activities.

As **D4.2** is a public (PU) deliverable, its contents have been prepared with specific attention to confidentiality, intellectual property (IP) protection, and Partner-sensitive information. The report does not disclose source code, detailed engineering drawings, full technical specifications, proprietary datasets, commercially sensitive operational information, or images from Partner facilities that have not been explicitly approved for public dissemination. Instead, it presents the work at an appropriate level of abstraction, focusing on the validation logic, technical progress, maturity status, and next steps for each sorting line.

Overall, this current report intends to provide a structured public account of the progress achieved in WP4 towards the development of TRL5-ready sorting lines. It also aims to establish the basis for the next development cycle, which will focus on deployment aspects and the transition of the sorting systems towards TRL6 in subsequent WP4 deliverables, namely **D4.3 "Sorting Lines (TRL6-ready)"** and **D4.4 "Sorting Lines (TRL7/8-ready)"**.

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Abbreviations

Abbreviations	Full name
D4.1	Deliverable 4.1 “Technologies Requirements”
D4.2	Deliverable 4.2 “Sorting Lines (TRL5-ready)”
D4.3	Deliverable 4.3 “Sorting Lines (TRL6-ready)”
D4.4	Deliverable 4.4 “Sorting Lines (TRL7/8-ready)”
EC	European Commission
EOAT	End-of-Arm Tooling
EU	European Union
FTIR	Fourier Transform Infrared Spectroscopy
H4C	Hub for Circularity
HADEA	European Health and Digital Executive Agency
HSI	Hyperspectral Imaging
ICCS	Institute of Communication and Computer Systems
IP	Intellectual Property
I-US	Industrial-Urban Symbiosis
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
NIR	Near-Infrared
PET	Polyethylene Terephthalate
PLC	Programmable Logic Controller
RGB	Red Green Blue
RGB-D	Red Green Blue with depth information
TRL	Technology Readiness Level

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WP	Work Package
WP4	Work Package 4 “Separation and sorting technologies”
XR	Extended Reality
XRF	X-ray Fluorescence
XRT	X-ray Transmission

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1 Introduction

1.1 The project: Theseus

Industrial-Urban Symbiosis (I-US) is a sustainability approach in which cities, regions, industries, infrastructure operators, and other territorial actors cooperate in order to optimize the use of resources, waste, energy, water, services, and transport systems. In this particular context, industrial and urban systems are not treated as isolated domains, but as interdependent parts of a wider circular ecosystem instead. This approach allows material and resource flows that would otherwise be significantly underutilized or discarded to be redirected towards new uses, thus supporting circularity, resource efficiency, and climate neutrality.

The Horizon Europe project "THESEUS" develops a first-of-a-kind Hub for Circularity (H4C) in Greece, starting from the capital region of Athens and Attica, with the ambition to support wider replication across the country and even beyond. The long-term aim of the project is to contribute to the realization of closed resource loops through I-US, aligned with European circular economy and climate neutrality objectives. THESEUS addresses water, energy, and material flows through a broad combination of technological solutions, considering and analyzing regional needs, digital tools, and new governance and collaboration models. Within THESEUS, material flow possesses a pivotal role, as it links waste generation, collection, sorting, separation, material recovery, upcycling, and reuse in industrial level. The sorting and separation procedures of secondary material streams is therefore considered a key enabling activity. Without achieving appropriate identification, classification, and separation of material fractions, subsequent valorization routes cannot receive the quality of inputs required for high-value reuse or upcycling reliably. THESEUS targets to address this challenge through multiple technical work packages. WP4 focuses specifically on separation and sorting technologies, whereas downstream activities further investigate the valorization and upcycling of recovered materials. In this sense, WP4 acts as an enabling connection between real-world waste and secondary material streams, and the circular material pathways pursued by THESEUS.

1.2 WP4: Separation and sorting technologies

WP4 contains the development and integration of advanced separation and sorting technologies to enhance the valorization of secondary material streams across distinct waste sources. It serves as one of the main technical pillars of the THESEUS, aiming to provide solid connections between material preparation, characterization, sensing, physical sorting, robotic manipulation, and plant-level optimization with downstream processing and upcycling activities. The work package covers a wide spectrum of material categories and processing environments. These environments include mixed urban waste from blue bins, textile waste, specific plastics recovery from mixed waste, metal scrap separation and recovery, and glass bottle sorting. Each of these distinct streams presents varying technical challenges. Indicatively, mixed urban waste is highly heterogeneous and frequently contaminated. Textile waste is deformable, often compositionally complex, and usually difficult to present consistently to sensing systems. Plastic recovery requires the robust identification and extraction of valuable polymer fractions from complex and often degraded streams. Metals separation requires robust identification and sorting of valuable metallic fractions. Glass sorting requires reliable inspection and handling under conditions where fragility, reflections, geometry, and throughput can become important constraints.

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The work of WP4 is organized across several tasks, covering both stream-specific sorting developments and cross-cutting supporting technologies. The relevant WP4 tasks are:

- Task 4.1 – Separation and sorting at multiple levels analysis and materials upcycling, optimization and design.
- Task 4.2 – Mixed urban waste separation
- Task 4.3 – Textiles sorting
- Task 4.4 – Plastics recovery from mixed waste
- Task 4.5 – Metals separation / Glass separation
- Task 4.6 – Resource optimization for symbiotic flows management at plant level
- Task 4.7 – Smart bins for Attika
- Task 4.8 – XR for human–robot interaction and collaboration

This WP plays a critical role in ensuring that THESEUS can deliver high-performance, adaptable, and scalable sorting systems, aligned with the overall goals of circularity, efficiency, and industrial integration.

1.3 The Deliverable: D4.2 Sorting Lines (TRL5-ready)

Deliverable **D4.2** comprises the first version of the THESEUS sorting line developments. It reflects the work carried out in **Tasks 4.2, 4.3, 4.4,** and **4.5** and focuses on the preliminary development and validation status of the sorting lines for mixed urban waste, textile sorting, plastics recovery, metals separation, and glass sorting. D4.2 is the first deliverable in a sequence of WP4 outputs dedicated to the progressive maturation of the sorting lines. It is followed by **D4.3 "Sorting Lines (TRL6-ready)"** and **D4.4 "Sorting Lines (TRL7/8-ready)"**. This structure aims to properly reflect the incremental development of the sorting solutions, from requirements and conceptual design, to TRL5 readiness, to deployment-oriented validation, and finally to higher maturity evaluation.

The purpose of **D4.2** is therefore to document the transition from the conceptual design phase reported in **D4.1** to the first implementation and validation phase. At this stage, the emphasis is placed on preliminary developments, module-level validation, sub-system feasibility, initial integration logic, and the identification of remaining technical and operational challenges before the next maturity step.

For the purposes of this deliverable, TRL5 readiness is interpreted as the availability of validated modules, sub-systems, or preliminary integrated prototypes demonstrated under controlled or representative conditions. For clarification purposes, the target at this point is not to claim full industrial deployment readiness. Instead, the aim is to show that the main technical principles of each sorting line have progressed beyond conceptual design and have been tested sufficiently to justify their continuation towards TRL6-oriented deployment activities. The deliverable follows a structured and consistent approach across the 5 sorting lines. Each line is presented in relation to its baseline from **D4.1**, its **D4.2** development objectives, the current public system concept, the validation activities performed or planned within the reporting scope, the current TRL5-readiness status, and the next steps required for further maturation.

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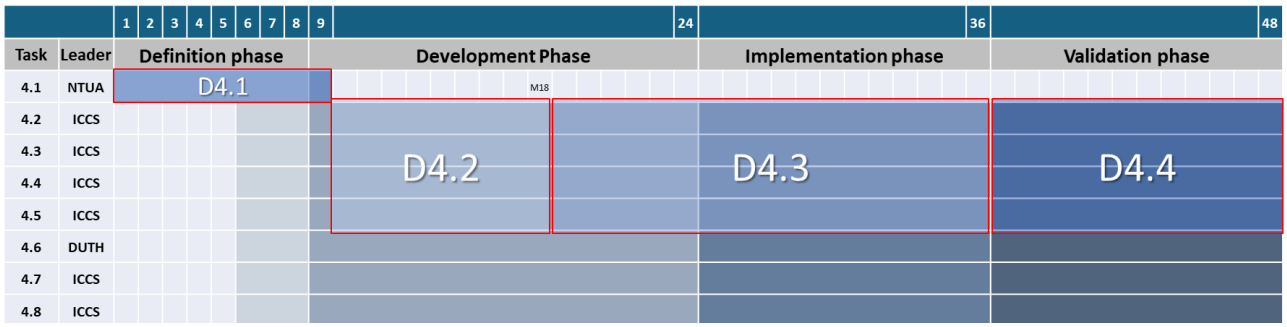


Figure 1: Role of D4.2 within the WP4 deliverable sequence

1.4 Relation between D4.2 and D4.1

Deliverable **D4.1** constitutes the precursor and serves as the main technical baseline for D4.2. D4.1 reported the requirements analysis, concept design, and preliminary optimization logic for the material and sorting solutions developed in **WP4**. It collected structured input from the relevant Partners, analyzed the needs and constraints of each sorting case, reviewed relevant sorting and upcycling approaches, and proposed conceptual designs for each of the 5 sorting lines developed within THESEUS. **D4.2** builds directly on this baseline. While **D4.1** focused on understanding what needs to be developed and why, **D4.2** focuses on how the first version of these developments is being translated into validated technical progress. In practical terms, the relationship between the two deliverables can be understood as follows: **D4.1** established the problem definition, the requirements, the constraints, and the initial concepts, while **D4.2** reports the first implementation and validation-oriented response to these requirements. This relationship is particularly important because the THESEUS sorting lines are not standalone technological demonstrations. They are developed to address specific material streams, Partner needs, downstream valorization requirements, and operational contexts. Thus, the validation activities reported in **D4.2** must correspond to the documented requirements and assumptions defined in **D4.1**. At the same time, **D4.2** also is expected to provide the first feedback loop to **D4.1**. During the transition from conceptual design to validation, certain assumptions may need to be refined, certain design options may prove more practical than others, and specific constraints may prove more important as laboratory or representative-environment testing progresses. This means that **D4.2** does not replace **D4.1**, but uses it as a reference point while also preparing the ground for the next maturity steps. Table 1 summarizes the main relationship between the two deliverables.

Table 1: Relationship summary between D4.1 and D4.2

Aspect	D4.1 Technologies Requirements	D4.2 Sorting Lines (TRL5-ready)
Target	Establish requirements, constraints, and conceptual designs.	Report preliminary developments and TRL5-readiness status.
Direction	Requirement- and concept-driven.	Development-driven and validation-driven.

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Evidence	Stakeholder input, requirements analysis, state-of-the-art review, conceptual layouts.	Module validation, sub-system validation, public maturity assessment, next-step planning.
Role within WP4	Baseline/Reference point for sorting technologies.	First maturity snapshot of the sorting line developments.
Link to next deliverables	Supports all subsequent WP4 sorting deliverables.	Supports transition towards D4.3 and TRL6 readiness.

1.5 Public dissemination boundaries

D4.2 is a public deliverable. This entails important implications for the level of information that can be disclosed. The sorting lines developed in THESEUS involve industrial Partners, operational environments, technical designs, datasets, material stream information, and system integration details that may be sensitive from a commercial, operational, intellectual property, or security point of view.

Due to this, **D4.2** presents the work at a controlled level of technical abstraction. It aims to retain an informative and useful point of view, while avoiding disclosure of information that could compromise Partner interests, future exploitation routes, facility confidentiality, or technical ownership. This current report thus focuses on objectives, methodology, public-safe architecture descriptions, validation logic, maturity status, and next steps. It does not include source code, detailed software implementation, full algorithmic descriptions, protected datasets, detailed engineering drawings, Partner facility images, procurement-sensitive information, or operational details that could expose the internal configuration of Partner sites. Wherever visual material is needed, the report uses generic diagrams, public-safe schematics, or placeholders for approved images. This approach is consistent with the public nature of the deliverable. It also supports a clearer distinction between the public reporting layer and the internal technical evidence base maintained by the consortium. More detailed material may exist internally to support technical decision-making, integration, and future validation, but it is not reproduced in this public document unless it has been confirmed as suitable for dissemination.

1.6 Structure of D4.2

Deliverable **D4.2** is structured to support a clear transition from project context and methodological framing to sorting-line-specific reporting and cross-line synthesis.

- **Section 1** introduces the THESEUS project, the role of WP4, the scope of D4.2, its relation to D4.1, the public dissemination boundaries, the intended readership, and the structure of the report.
- **Section 2** presents the methodological framework used for assessing TRL5 readiness. It defines how TRL5 readiness is interpreted in **D4.2**, introduces the validation dimensions applied across the sorting lines, and explains the type of evidence used in this public deliverable.

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- **Sections 3** to **6** present the five sorting line developments addressed in **D4.2**. Each section follows a common reporting logic, covering the baseline from **D4.1**, the development objectives, the current public system concept, validation activities, TRL5-readiness status, open issues, and next steps.
- **Section 7** provides a cross-line synthesis. It consolidates the readiness status of all sorting lines, identifies common findings and challenges, and discusses alignment with downstream valorization and upcycling pathways. It also concludes the deliverable by summarizing the main outcomes and presenting the next steps towards TRL6 and D4.3.

1.7 Intended readership of D4.2

D4.2 is intended for multiple audiences. Its primary audience is the THESEUS consortium, as the report provides a common reference for the maturity status of the WP4 sorting lines and supports coordination between technical Partners, pilot hosts, and downstream material valorization activities. It is also intended for HADEA and the European Commission, as it documents progress against the Grant Agreement and provides evidence of the first development step towards TRL5-ready sorting lines. Since the deliverable is public, it may also be accessed by other EU-funded projects, industrial stakeholders, research organizations, circular economy actors, public authorities, and the general public. For these audiences, the report provides an overview of the approach followed by THESEUS in developing sorting technologies within a H4C context. However, due to the dissemination boundaries explained above, the deliverable should not be interpreted as a technical manual or as a full disclosure of the internal engineering work carried out by the consortium.

Table 2: Intended readership

Target	Description
THESEUS Partners	To serve as a shared technical reference for the first development and validation status of the **WP4** sorting lines. The deliverable supports internal alignment between sorting activities, downstream material valorization tasks, and future deployment planning.
HADEA / European Commission	To provide evidence of progress against the Grant Agreement and to document the first maturity step of the sorting line developments towards TRL5 readiness.
Other EU-funded projects under similar thematic areas	To provide a public overview of the methodology followed by THESEUS for developing and validating sorting lines in the context of circular material flows and Hubs for Circularity.
Industrial and circular economy stakeholders	To communicate the general approach, maturity status, and expected development pathway of the THESEUS sorting technologies without disclosing sensitive technical or operational information.

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2 Methodological framework for TRL5 readiness

2.1 From conceptual design to TRL5 readiness

The development of the THESEUS sorting lines follows a multi-stage maturity pathway. This pathway begins from the requirements analysis and conceptual design activities reported in **D4.1** and progresses towards the preliminary development and validation activities reported in the present deliverable. In the next stages of **WP4**, this work will evolve further towards TRL6-ready deployment and subsequently towards higher maturity evaluation in relevant or operational environments. **D4.1** established the foundation for this process. It analyzed the real-world constraints, material characteristics, Partner needs, and operational requirements of the sorting lines to be developed within THESEUS. It also proposed the conceptual design baseline for each sorting case, covering mixed urban waste, textile waste, plastics recovery from mixed waste, metals separation, and glass sorting. **D4.2** builds on this baseline and reports the first step in translating the conceptual designs into preliminary validated sorting solutions. It is followed by **D4.3**, which focuses on deployment aspects for TRL6-ready sorting lines, and finally **D4.4**, which focuses on evaluation towards TRL7/8-ready sorting lines. This sequence creates a clear development logic: **D4.1** defines the baseline, **D4.2** validates the first version of the technical solutions, **D4.3** moves the systems closer to deployment, and **D4.4** evaluates the implementation in its maturity.

Within this framework, **D4.2** should not be interpreted as a final validation report. It is rather the first maturity snapshot of the sorting technologies. Its purpose is to document that the main technological directions have progressed beyond concept definition and have entered a first validation phase. At this stage, the emphasis is placed on the validation of key modules, early sub-systems, laboratory or representative-environment tests, and the confirmation that the selected technological routes remain feasible for further development. This staged approach is particularly relevant for THESEUS because the sorting lines address different material streams and operational contexts. The same validation logic cannot be applied identically to all cases. Indicatively, Textile sorting requires particular attention to material presentation, deformation, and fibre composition recognition. Mixed urban waste and plastics recovery require robust handling of highly heterogeneous, contaminated, and irregular items. Metals sorting requires reliable identification and separation of valuable metallic fractions. Glass sorting requires precise inspection and handling strategies compatible with fragile and reflective items.

For this reason, **D4.2** adopts a common methodological framework, but allows the specific validation evidence to differ between sorting lines. The common framework ensures consistency in reporting, while the line-specific chapters allow the validation activities to reflect the technical reality of each stream.

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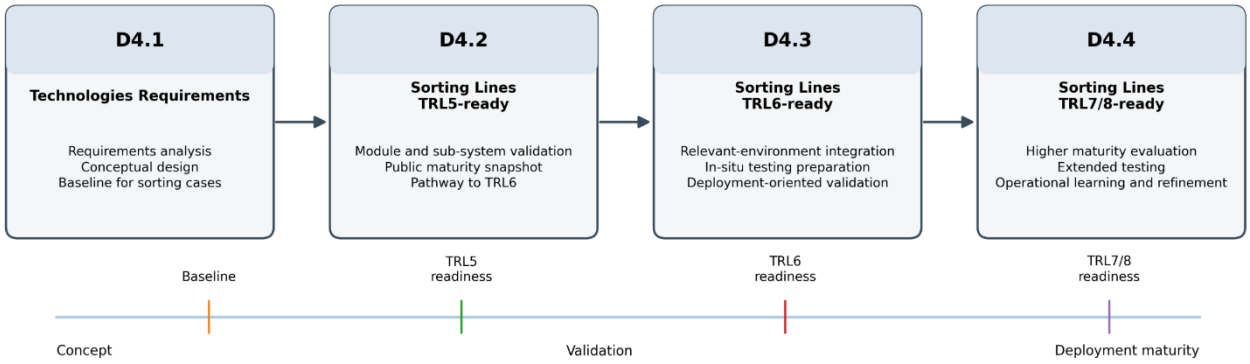


Figure 2: Progression from conceptual design to TRL5, TRL6 readiness, and TRL7/8 evaluation

2.2 Working definition of TRL5 readiness in D4.2

For the purposes of this deliverable, TRL5 readiness is interpreted as the availability of a technically defined sorting concept, supported by preliminary validation evidence under controlled or representative conditions. This may refer to validated modules, tested sub-systems, laboratory trials, representative sample tests, or integration-oriented design activities. TRL5 readiness in D4.2 does not imply that the complete sorting line has been installed and operated at the final host site. It also does not imply that all technical parameters have been finalized. Instead, it indicates that the main technological direction is sufficiently mature to justify continuation towards TRL6-oriented deployment work. This interpretation is necessary because the THESEUS sorting lines are composed of several interacting parts. Depending on the case, these may include material feeding, sensing, classification, decision-making, actuation, material extraction, collection, safety provisions, and integration with the wider material flow. At the D4.2 stage, not all parts are expected to have reached the same maturity level. Therefore, the assessment of TRL5 readiness is based on the following practical criteria:

Table 3: Working interpretation of TRL5 readiness in D4.2

Criterion	Interpretation in D4.2
Concept maturity	The sorting concept has progressed beyond the conceptual design reported in D4.1.
Technical feasibility	The key sensing, classification, handling, or sorting principle has been tested or assessed.
Representative relevance	The validation activities are linked to the intended material stream or use case.
Pathway to TRL6	The next technical steps, integration needs, and open issues have been identified.

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2.3 Validation approach

In order to retain consistency of the assessment across the sorting lines, **D4.2** uses 4 validation pillars. These pillars were selected to be broad enough to cover all material streams, while remaining practical for the current reporting stage.

1. The first pillar refers to **functional feasibility**. This concerns whether the proposed sorting approach can perform its intended basic function. Depending on the line, this may involve detecting target items, identifying material categories, handling representative objects, redirecting material fractions, or demonstrating the main sorting sequence.
2. The second pillar is **technical module validation**. This concerns the maturity of the key technical modules. These may include sensing, classification, actuation, feeding, item presentation, or control logic. At **D4.2** level, the objective is to show that the main technological principles are feasible, even if full integration remains part of the next phase.
3. The third pillar is **integration readiness**. This concerns whether the main modules can reasonably be combined into a coherent sorting system. It includes the definition of the public system architecture, the expected information flow, the interaction between sensing and actuation, and the identification of remaining integration needs.
4. The fourth pillar concerns **deployment awareness**. This refers to practical issues that must be absolutely addressed in order to move towards TRL6. These issues include industrial robustness, safety, facility constraints, material variability, environmental conditions, maintenance, and alignment with downstream valorization pathways.

Table 4 provides a tabularized summary of the validation pillars used in D4.2.

Table 4: Validation pillars used across the sorting lines

Validation pillar	Description	Typical D4.2 evidence
Functional feasibility	Demonstrates that the intended sorting function is technically plausible and has been tested at a preliminary level.	Laboratory trials, sample tests, preliminary demonstrations, qualitative findings.
Technical module validation	Assesses the maturity of the key sensing, classification, handling, or sorting modules.	Module tests, sensor trials, handling tests, preliminary performance summaries.
Integration readiness	Assesses whether the modules can be combined into a coherent sorting line.	High-level architecture, interface logic, integration planning, partial combined tests where available.
Deployment awareness	Identifies open issues before TRL6-oriented deployment.	Risk notes, constraints, next steps, safety and operational considerations.

2.4 Evidence types and reporting approach

The evidence used in D4.2 is grouped into 3 categories. The first category comprises **design evidence**. This includes the evolution of the concepts from **D4.1** into more concrete sorting architectures, module

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definitions, process flows, and integration plans. In the public version of D4.2, this evidence is presented through high-level descriptions and schematic placeholders. The second category is **validation evidence**. This includes the results of preliminary tests, representative sample trials, sensing or handling assessments, and module-level demonstrations. Since **D4.2** is public, validation evidence is reported in a summarized way. Detailed datasets, source code, sensitive technical settings, and proprietary algorithmic information are not included. The third category is **maturity evidence**. This includes the assessment of current status, open issues, technical risks, and next steps towards TRL6. This type of evidence is especially important for D4.2, because the deliverable acts as a transition point between conceptual design and deployment-oriented development. Table 5 sums up the evidence types used in the deliverable.

Table 5: Evidence types used in D4.2

Evidence type	Purpose	Public reporting approach
Design evidence	Shows how the D4.1 concepts have evolved into technical development pathways.	High-level descriptions, public-safe diagrams, module summaries.
Validation evidence	Shows that key technical principles have been tested or assessed.	Aggregated results, qualitative findings, non-sensitive validation summaries.
Maturity evidence	Shows the current readiness level and the path towards TRL6.	Readiness tables, open issues, risks, and next steps.

2.5 Common reporting template for the sorting lines

Due to their similarity in structure **Sections 3** to **7** follow a common reporting structure. This ensures consistency between the sorting lines, while allowing the content of each chapter to reflect the actual progress achieved for each stream. More specifically, each sorting line chapter includes 5 main parts. First, the baseline from D4.1 is briefly recalled. This explains the role of the line and the main concept that was defined in the previous deliverable. Second, the D4.2 development objectives are presented. These objectives describe what the consortium aimed to advance during this first validation phase. Subsequently, the current public system concept is described. This includes the main modules and the expected process flow, without disclosing sensitive technical information. Fourth, the validation activities and current status are summarized. This part presents the available evidence at a level appropriate for a public deliverable. Last but not least, the open issues and next steps are identified. This prepares the transition towards TRL6 and D4.3. Table 6 presents the common reporting structure used in the line-specific chapters in a more compact form.

Table 6: Common reporting structure for each sorting line

Chapter part	Purpose
Baseline from D4.1	Recalls the starting point and concept basis.
D4.2 development objectives	Defines the purpose of the first validation phase.

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Current public system concept	Describes the sorting approach at a public-safe level.
Validation activities and current status	Summarizes the available evidence and maturity status.
Open issues and next steps	Identifies what remains before TRL6-oriented deployment.

Additionally, to support a clear and realistic assessment, D4.2 uses a simple qualitative maturity scale as depicted on Table 7.

Table 7: Qualitative maturity scale used in D4.2

Status	Interpretation
Initiated	Development has started, but validation evidence remains limited.
Under validation	Preliminary tests or assessments are ongoing.
Partially validated	Feasibility has been shown, but additional work is required.
TRL5-ready for current scope	Sufficient evidence exists to support continuation towards TRL6 work.
Pending TRL6 deployment	The next step is deployment-oriented integration and testing.

3 Mixed urban waste and plastics sorting lines

3.1 Baseline and development

The mixed urban waste and plastics recovery sorting platform sorting cases represent two of the central robotic sorting developments of WP4. In **D4.1**, the mixed recyclable urban waste sorting line was defined as a data-driven robotic extraction system intended to enhance the recovery of selected material fractions from an existing mixed waste processing environment. The original concept was based on two main modules: a sensing unit installed upstream of the robotic intervention point and a robotic extraction unit positioned downstream, both adapted to the existing geometry and constraints of the host facility. The target stream is highly heterogeneous and includes material fractions such as plastics, paper, cardboard, metals, glass, and other residuals. The sorting challenge is therefore not limited to the recognition of one material category, but concerns the detection, classification, and extraction of selected recoverable fractions from a complex and variable stream. This creates the need for a flexible robotic platform that can be adapted to different sorting scenarios, material targets, and end-effector configurations.

In the current development phase, the work of **T4.2** and **T4.4** is treated through a common robotic sorting platform. This approach reflects the practical and technical overlap between the two tasks. Both tasks rely on visual and spectral sensing, object localization, robotic extraction, and deposition into dedicated collection areas. The main difference lies in the sorting scenario and in the selected end-effector. T4.2 focuses on mixed urban waste sorting and the extraction of different material fractions using a compliant finger-based gripping approach. **T4.4** focuses specifically on plastics recovery from mixed waste and uses a high-speed pneumatic suction approach more appropriate for bottles, bags, and packaging items.

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This shared implementation strategy reduces duplication and supports a more modular development pathway. The same robotic cell can be used to validate different sorting scenarios by changing the end-effector, adapting the sorting targets, and modifying the downstream deposition logic. This is especially important at TRL5 stage, where the objective is to validate the main technological principles and prepare the transition towards in-situ TRL6 operation.

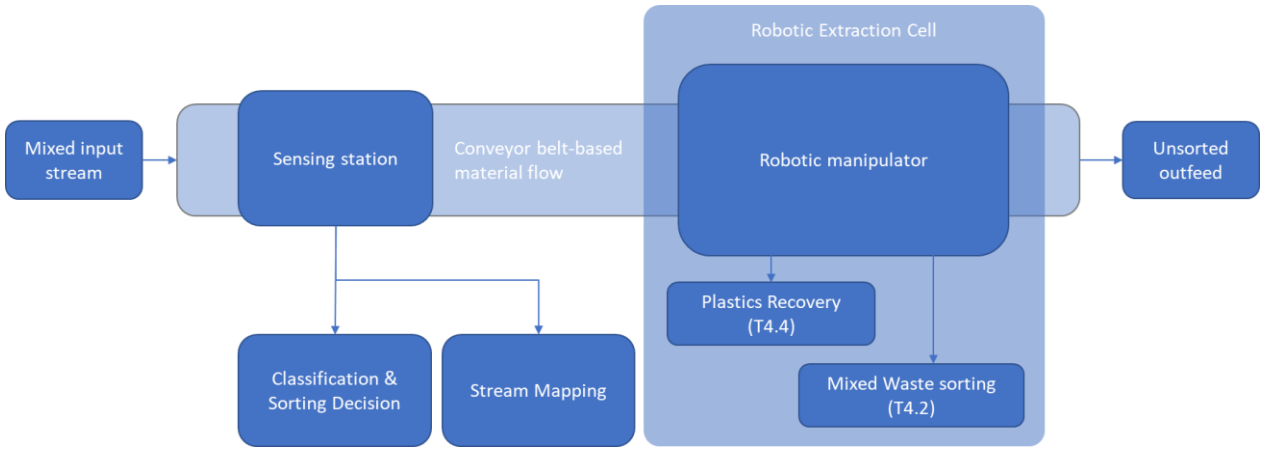


Figure 3: High-level concept of the shared mixed urban waste robotic sorting platform for T4.2 and T4.4

3.2 Current system concept and implementation status

The current laboratory setup consists of a conveyor belt, a sensing station, and a robotic manipulation system. The sensing station integrates RGB-D and hyperspectral imaging units, enabling the acquisition of both geometric and material-related information from objects moving on the conveyor. The robotic system is based on a collaborative robotic arm, which is used to validate the manipulation and extraction logic under laboratory conditions. For the mixed urban waste sorting scenario, the robot was initially equipped with a commercial two-finger gripper. The standard rigid fingertips were subsequently replaced by custom compliant fin-ray type fingers. This modification was introduced to improve the interaction of the gripper with irregular waste objects. The tailored compliance allows the fingers to conform more effectively to non-uniform geometries and supports safer and more robust grasping of mixed items. For the plastics recovery scenario, the selected end-effector is a pneumatic vacuum-based EOAT. This configuration is intended for high-speed extraction of plastic objects such as bottles, plastic bags, and packaging. Initial validation of this suction-based approach has been performed using an available delta robot setup. Although the laboratory demonstration was performed on a different robot platform, the developed software and sorting logic are designed to remain robot-agnostic and adaptable to different robotic systems, including the sorting robotic cell. The final implementation is planned around an overhead robotic configuration above the conveyor belt. This configuration was selected to fit the available selected sorting position and to allow direct extraction of selected items from the moving stream. The robotic platform will be supported by dedicated structural elements, while the deposition bins and extraction paths will be adapted to the facility layout. The sensing system ordered for these developments will initially support stream mapping and data collection. Once the robotic cell is integrated, the same sensing concept will also support the real-time sorting function. Table 8 below summarizes the current implementation status of the shared platform.

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Table 8: Current implementation status of the shared robotic sorting platform

Module	Current status	Role in T4.2 and T4.4
Conveyor-based laboratory setup	Available and used for preliminary validation	Supports controlled testing of sensing and robotic extraction
RGB-D sensing	Integrated in laboratory sensing station	Provides geometric and localization information
Hyperspectral imaging	Integrated in laboratory sensing station	Supports material-related classification and stream analysis
Collaborative robot	Available and used in laboratory trials	Main robotic platform for validation of the sorting cell
commercial two-finger gripper	Integrated and tested	Baseline gripper for mixed urban waste extraction
Custom fin-ray fingers	Designed, integrated, and tested	Improve compliance for irregular waste objects
Pneumatic suction gripper	Tested in separate robotic setup	Used for plastics recovery scenario
Data collection system	Ordered / under preparation	Will support stream mapping and later sensing operation in situ
In situ structural integration	Pending	Required for TRL6 deployment
Deposition bins and extraction paths	Under design / adaptation	Required for safe and practical in-situ operation

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Figure 5: Indicative laboratory validation setup with conveyor and robotic manipulation system



Figure 4: (left) Mixed waste EOAT configuration with compliant fin-ray fingers, (right) Plastics recovery EOAT configuration with suction cup

3.3 Validation activities and TRL5-readiness status

The validation activities performed so far focused on confirming the feasibility of the main technological principles required for TRL5 readiness. These activities include sensing pipeline validation, robotic pick-and-place trials, end-effector evaluation, and preliminary software integration. The sensing pipeline is currently established within the development team. The combined use of RGB-D and hyperspectral imaging supports the acquisition of complementary information from the passing stream. RGB-D data provides object localization and geometric information, while hyperspectral imaging supports material-level analysis. This

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combination is aligned with the original **D4.1** concept and provides a suitable basis for both mixed urban waste sorting and plastic recovery.

With regard to the mixed urban waste scenario, laboratory tests were performed using the collaborative robot and the compliant fin-ray gripping configuration. Different types of representative items were picked from the conveyor in order to assess the feasibility of robotic extraction. The tests confirmed that the compliant fingers provide improved adaptability compared with rigid fingertip configurations, particularly when interacting with irregular, non-uniform, or deformable objects. Internal validation material has been generated to support the technical record.

With consideration to the plastics recovery scenario, preliminary validation was performed using the pneumatic suction gripper mounted on an available delta robot. The tests focused on the pick-up of representative plastic items, including bottles, bags, and packaging. This configuration is relevant to the final plastics recovery scenario because the end-effector principle and software logic are intended to be transferable to the shared platform. The robot-agnostic nature of the developed software supports this transfer, although final validation on the robotic cell on site remains part of the next phase.

The current validation results indicate that the platform has reached TRL5 readiness for the current scope. The main sensing, classification, and robotic extraction principles have been demonstrated under laboratory or representative conditions. The system has not yet been operated at final industrial speed with the final in-situ configuration. This limitation is mainly related to safety considerations and to the fact that the final structural integration at the line host's premises is still pending. Simulation-based estimates indicate the potential for high-throughput robotic sorting, pending experimental validation at final operating conditions. The involved working group is currently working on object clutter scenarios in order to validate the system under conditions closer to the intended operational environment. This is an important intermediate step between isolated object trials and in-situ operation on the line. Table 9 summarizes the current validation and maturity status in a concise manner.

Table 9: TRL5-readiness assessment for the shared sorting platform

Validation element	Current status	Evidence type	Assessment
Sensing pipeline	Established	Laboratory sensing setup with RGB-D and hyperspectral imaging	TRL5-ready for current scope
Mixed waste gripping	Tested with collaborative robot arm and compliant EOAT.	Laboratory pick trials with representative items	TRL5-ready for current scope
Plastics suction gripping	Tested on available delta robot setup.	Preliminary pick trials with representative plastic items	TRL5-ready, transferable to shared platform
Software adaptability	Developed with transferability between robotic platforms in mind logic.	Demonstrated transfer potential between robotic platforms	TRL5-ready

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Overall performance	Consistent performance (sensing and picking success rates) under continuous operation on short cycles.	Aggregated preliminary results	TRL5-ready for current scope
Throughput potential	High-throughput potential based on simulation	Simulation-based estimate	TRL5-ready, pending experimental validation at higher speeds
Object clutter handling	Ongoing	Near-real-condition validation under preparation	TRL5-ready in short cycle, longer continuous operation under validation

Based on the above, the mixed and plastic waste sorting platform is considered TRL5-ready for the current reporting scope. This assessment reflects the validation of the key technical principles under controlled or representative conditions. Full-speed operation, final structural installation, and in-situ testing remain part of the transition towards TRL6.

3.4 Open issues and next steps towards TRL6

The next development phase will focus on the transition from laboratory validation to deployment and on-site operation. The first main activity will be the construction and installation of the necessary structural elements to mount and house the robot above the conveyor belt. This includes the mechanical support structure, the intricate mounting configuration, provisions for access, and all necessary adaptations for safe operation within the designated sorting area. The deposition containers for each sorted fraction and extraction paths must also be finalized. Their design must allow the robot to deposit the selected fractions efficiently, without interfering with the normal operation of the facility. Particular attention will also be required for the subsequent routing of extracted materials, the eventual removal of filled containers, and the prevention of bottlenecks around the robotic cell. A further next step is the installation of the data collection system at the host's premises. Initially, this system will be utilized to map the real waste stream and generate representative data under actual operating conditions. This will provide a more accurate understanding of object distribution in the mixed stream, encountered material categories, clutter, flow variability, and other environmental effects. Following the integration of the robotic cell, the same sensing station and approach is expected to support the sorting function itself as the localization and classification module.

The main remaining technical challenge includes the validation of the complete system under real stream and environmental conditions. While laboratory trials and simulations have confirmed the feasibility of the approach, additional testing is required to assess performance under the true industrial constraints. These include moving cluttered objects, overlapping items, potentially variable lighting, presence of dust, contamination, vibration, and continuous, uninterrupted operation. Safety also presents a key issue for the next phase. Although the selected robotic manipulator is collaborative in nature, and its selection considered this specific feature for the same reason, the final installation will be placed in a waste processing environment with personnel access, moving conveyors, extraction bins, and potential maintenance operations. Therefore, strict safety precautions must be defined for both personnel and equipment. These may include physical guarding, restricted access zones, emergency stop provisions, operating procedures and guidelines, as well as protective measures for the robot and end-effectors. The deployment environment is

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also relatively harsh due to dust, dirt, and material variability, so protection measures of the robot, gripper, sensors, and cabling such as industrial-grade covers must be considered.

Table 10: Next steps towards TRL6 for the mixed urban waste and plastics sorting platform

Next step	Purpose
Build and install the robot support structure	Enable overhead robotic configuration above the conveyor.
Finalize deposition bins and extraction paths	Support safe and efficient collection of extracted fractions
Install the data collection system on site of the line host.	Map the real stream and generate representative operational data
Validate object clutter scenarios	Bridge laboratory tests with near-real operating conditions
Transfer plastics suction scenario to the shared platform	Validate T4.4 on the final robotic configuration
Increase experimental operating speeds	Compare laboratory operation with simulated throughput potential
Define safety measures	Protect personnel and ensure controlled robot operation
Protect robot, EOAT, sensors, and cabling	Improve robustness in a dirty and demanding MRF environment
Start in-situ trials	Move from TRL5-ready status towards TRL6 validation

Overall, the sorting platform has progressed from the **D4.1** concept into a validated laboratory-scale robotic sorting setup. The shared platform approach supports both the mixed urban waste scenario of **T4.2** and the plastics recovery scenario of **T4.4**. The current evidence supports TRL5 readiness for the scope of **D4.2**, while the next phase will focus on structural integration, in-situ sensing, higher-speed testing, and real-environment validation at the line host's facilities.

4 Textile sorting line

4.1 Baseline and development

The textile sorting line addresses the automated classification and separation of post-consumer textile items according to their material composition. In **D4.1**, the textile sorting case was defined as a dedicated sorting line based on spectral sensing, conveyor-based material flow, and selective ejection of textile items into predefined output categories. The main technical objective is to support the recovery of textile fractions with sufficient compositional quality for downstream valorization and upcycling activities within THESEUS. The

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sorting of textile waste presents specific challenges compared with more rigid and geometrically stable waste streams. Garments are flexible, deformable, frequently folded, and often overlapping. Their surface condition, colour, thickness, moisture, and fibre blend composition can affect sensing and classification. In addition, textile items are not naturally presented as isolated objects on a conveyor. This creates the need for a controlled feeding and singulation strategy before sensing and sorting can be performed reliably.

The current development focuses on PET-cotton textile blends. These blends are relevant because they represent an important part of post-consumer textile waste and because their separation by composition can support more targeted recycling and upcycling pathways. For the current TRL5 phase, the work is based on ground-truth textile specimens representing defined PET-cotton blend ratios. These specimens provide a controlled basis for evaluating the sensing, classification, and sorting logic before moving towards larger-scale testing with real textile waste on site. The development approach follows the conceptual logic introduced in **D4.1**, while adapting it to the practical validation work carried out at ICCS premises. The first version of the line is therefore implemented as a laboratory-scale system that combines conveyor-based transport, spectral sensing, and air-nozzle-based ejection. This setup is used to validate the main sorting principle before the procurement and installation of an extended sorting line at the line host's premises.

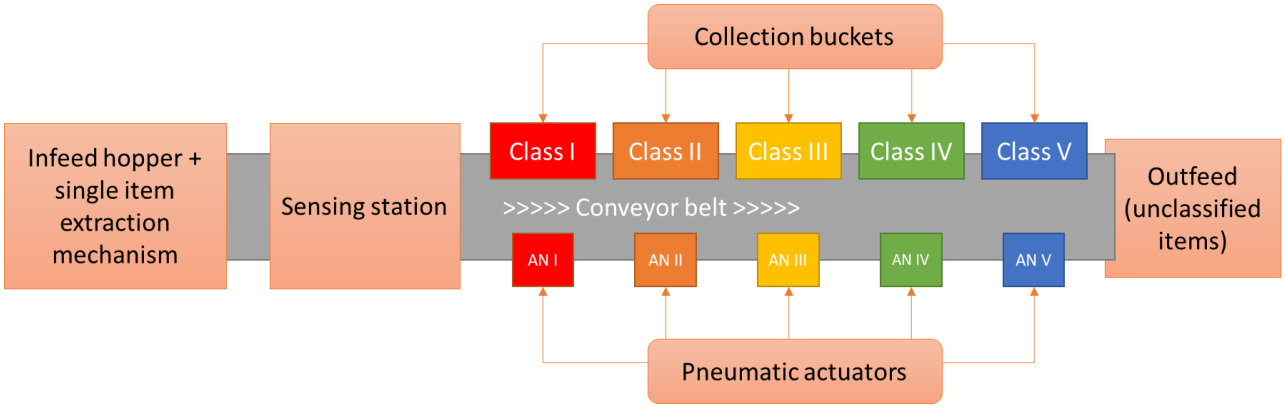


Figure 6: High-level concept of the textile sorting line from feeding to sensing and category-based ejection

4.2 Current system concept and implementation status

The current textile sorting setup is located at ICCS premises and consists of a conveyor-based test line, a sensing station, and an air-nozzle ejection module. Textile items are transported under the sensing station, where their material composition is assessed. When an item is assigned to a selected category, the air nozzle setup is activated and the garment is redirected sideways towards a side collection container. This setup validates the core sorting principle, which is to detect the textile item, classify it according to its material composition, and remove it from the main conveyor flow through a non-contact ejection mechanism. The use of air nozzles is suitable for the current validation stage because it allows fast actuation and avoids direct mechanical interaction with flexible garments during the ejection step.

A key development need concerns the feeding of textile items. Since garments tend to arrive in piles or overlapping configurations, a two-stage singulation mechanism is planned. The first stage will consist of a vertical mechanical gripping module intended to lift individual or partially separated garments from an infeed pile. The second stage will consist of a horizontal transfer module that will re-grasp the garment and release

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it onto the conveyor as a single item. This approach is intended to improve the consistency of material presentation before sensing and classification. The current laboratory setup is used for proof-of-concept and TRL5 validation activities. In the next phase, an extended sorting line will be procured and installed at the host's premises. The laboratory-proven air-nozzle separation module will be replicated and integrated into the extended line a number of times corresponding to the sorting categories. The current plan is to clone the nozzle separation module four additional times, so that multiple sorting categories can be addressed along the conveyor. This staged implementation allows the involved working group to first validate the fundamental sensing and ejection logic, and then expand the architecture towards a complete multi-category sorting line. The current implementation status of the textile sorting line is also summarized in Table 11.

Table 11: Current implementation status of the textile sorting line

Module	Current status	Role in the textile sorting line
Conveyor-based laboratory setup	Available at ICCS premises and used in trials	Controlled textile circulation under the sensing station.
Sensing station	Available and used in trials	Material composition assessment of textiles.
Ground-truth textile specimens	Procured and used in experiments	Provide controlled PET-cotton blend reference categories.
Air-nozzle ejection module	Available and tested	Redirects selected textile items into a side collection container.
Side collection container	Available in laboratory setup and tested	Receives ejected textile items during validation trials
Two-stage singulation mechanism	Under development	Intended to separate garments from the infeed pile and present single items on the conveyor.

4.3 Validation activities and TRL5-readiness status

The validation activities performed so far focus on the feasibility of the main textile sorting sequence. The work includes ground-truth specimen preparation and analysis, sensing trials, conveyor-based item presentation, and air-nozzle ejection tests. Ground-truth specimens have been procured for defined PET-cotton blend categories. The current reference categories cover five reference blend ratios. These categories support the controlled evaluation of the sensing and classification approach. They also provide a practical basis for assessing how well the system can distinguish textile compositions that are relevant for downstream material valorization. The experimental work has included the investigation of more than 50 pieces of clothing under the sensing station. These trials were used to assess the interaction between textile presentation, sensing, classification, and pneumatic ejection. Selected garments were redirected from the conveyor using the air-nozzle setup and collected in a container placed at the side of the conveyor. The tests confirmed the feasibility of the basic sorting principle at laboratory scale.

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The validation work has so far combined individual module trials with proof-of-concept pipeline tests. Individual trials were used to evaluate specific parts of the process, such as sensing, conveyor transport, and air ejection. Combined tests were also performed to demonstrate the full pipeline that includes passing a garment under the sensing station and triggering the ejection mechanism. At this stage, the combined pipeline has been validated mainly at proof-of-concept level, while systematic multi-category testing remains part of the next development phase. The current sensing and classification results are considered sufficient to support TRL5 readiness for the present scope. The validation and maturity status of the textile sorting line is additionally summarized below in Table 12.

Table 12: TRL5-readiness assessment for the textile sorting line

Validation element	Current status	Evidence type	Assessment
Ground-truth specimens	Procured and used in trials	PET-cotton reference categories	TRL5-ready for current scope
Textile categories	Defined for PET-cotton blends	5 reference blend ratios	TRL5-ready for current scope
Sensing station	Used in laboratory trials	More than 50 textile items passed under the sensing station	TRL5-ready for current scope
Classification performance	Consistent classification accuracy under continuous operation in short working cycles.	Aggregated preliminary results and laboratory trials at ICCS premises.	TRL5-ready for current scope
Air-nozzle ejection	Tested with selected garments	Side ejection into collection container	TRL5-ready for current scope
Combined sorting pipeline	Demonstrated at proof-of-concept level	Sensing-to-ejection trial sequence	TRL5-ready for current scope
Two-stage singulation mechanism	Planned / under development	Design concept defined	Pending next development phase

Based on the above, the textile sorting line is considered TRL5-ready for the current reporting scope. The main sensing and ejection principles have been demonstrated at laboratory scale, using controlled textile specimens and a conveyor-based test setup. The full multi-category line, including repeated nozzle modules and improved garment singulation, will be developed and validated in the next phase.

4.4 Open issues and next steps towards TRL6

The next phase will focus on expanding the current proof-of-concept setup into a complete sorting line suitable for installation and validation at the line host's premises. The most important step is the procurement and installation of the extended sorting line. This line will allow the laboratory-proven principles

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to be tested under realistic operating conditions and with a higher degree of system integration. A central remaining open issue is garment decluttering and singulation. Reliable classification and ejection require textile items to be presented individually and with sufficient spacing. In real textile waste streams, garments are expected to arrive folded, entangled, or stacked. The planned two-stage feeding mechanism is therefore important for the transition towards TRL6. The vertical gripping module will support the extraction of garments from the infeed pile, while a horizontal transfer module will support controlled release onto the conveyor.

An additional key next step is the replication of the air-nozzle separation module. The current setup demonstrates the ejection of selected items into a side container. For multi-category sorting, this module will be replicated and placed at multiple consecutive positions along the sorting line. Each module will correspond to a defined sorting category or output stream. This will allow the system to move from single-category proof-of-concept testing towards complete category-based textile sorting. Further validation will also be required for classification performance across a larger and more diverse textile dataset. The current ground-truth specimens provide a controlled basis for TRL5 validation, but additional testing with more variable textile items will be required. This will include variations in colour, texture, thickness, folding, surface condition, and garment type. Such testing will improve the robustness of the sensing and classification pipeline before in-situ trials. Last, but not least the eventual industrial integration will also require practical consideration of safety, accessibility, maintenance, and material handling. The placement of the line, the collection containers, the air supply, the control system, and the operator interaction points must be defined in a way that supports safe and practical operation.

Table 13: Next steps towards TRL6 for the textile sorting line

Next step	Purpose
Complete further laboratory validation at ICCS	Consolidate sensing, classification, and ejection performance
Develop the two-stage singulation mechanism	Improve garment separation and controlled conveyor presentation
Procure the extended sorting line	Enable larger-scale and more integrated testing
Install the line at the Partner's premises	Move from laboratory validation to relevant-environment testing
Replicate the air-nozzle separation module	Enable multi-category textile sorting
Expand testing beyond ground-truth specimens	Improve robustness against real textile variability
Integrate category-based collection containers	Support practical separation of textile output streams
Define safety and operational procedures	Prepare the system for TRL6-oriented operation

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Overall, the textile sorting line has progressed from the conceptual design reported in **D4.1** to a laboratory-scale sorting setup combining conveyor transport, sensing, and air-nozzle ejection. The current evidence supports TRL5 readiness for the **D4.2** scope. The next stage will focus on item singulation, multi-category ejection, extended line procurement, and on-site validation.

5 Metals sorting line

5.1 Baseline and development

The metals sorting line addresses the identification and separation of selected copper-containing material fractions from the metal scrap stream associated with the metals recycling Partner. In **D4.1**, the metals sorting case was defined as a dedicated sorting line intended to support the recovery of higher-value metallic fractions through a sensing-based and automated separation approach. The main technical objective is to distinguish pieces of pure or sufficiently clean copper from pieces containing contaminants or non-target material characteristics. This separation is relevant because the quality of the recovered metallic fraction directly affects downstream processing, material value, and the overall efficiency of circular material flows within THESEUS. Compared with lighter material streams, such as textiles or plastics, the metal sorting case presents different technical requirements. Metal pieces may vary significantly in geometry, size, surface oxidation, contamination, and presentation on the conveyor. In addition, the final solution must be compatible with an industrial environment where robustness, safety, and reliability are essential. Therefore, the current development phase focuses on identifying a sensing approach that is technically suitable, practical for integration, and capable of supporting fast actuation-based separation.

The work carried out so far has focused on laboratory-based evaluation using samples provided by the eventual line host, combined with site assessment activities to understand the future integration context. Several sensing approaches were investigated during this first development phase, including hyperspectral imaging (HSI), X-ray fluorescence (XRF), and Fourier-transform infrared (FTIR) spectroscopy. Additional experiments using X-ray transmission (XRT) are also under consideration, although implementation constraints must be assessed carefully before selecting it for deployment-oriented work. Based on the work performed so far, HSI has emerged as the most suitable sensing route for the first version of the metals sorting line. The selected system concept therefore consists of a conveyor-based sorting line, a sensing station based on hyperspectral imaging, and pneumatic separation module. The pneumatic ejection system will be used to redirect selected metal pieces from the main conveyor flow into a dedicated collection area.

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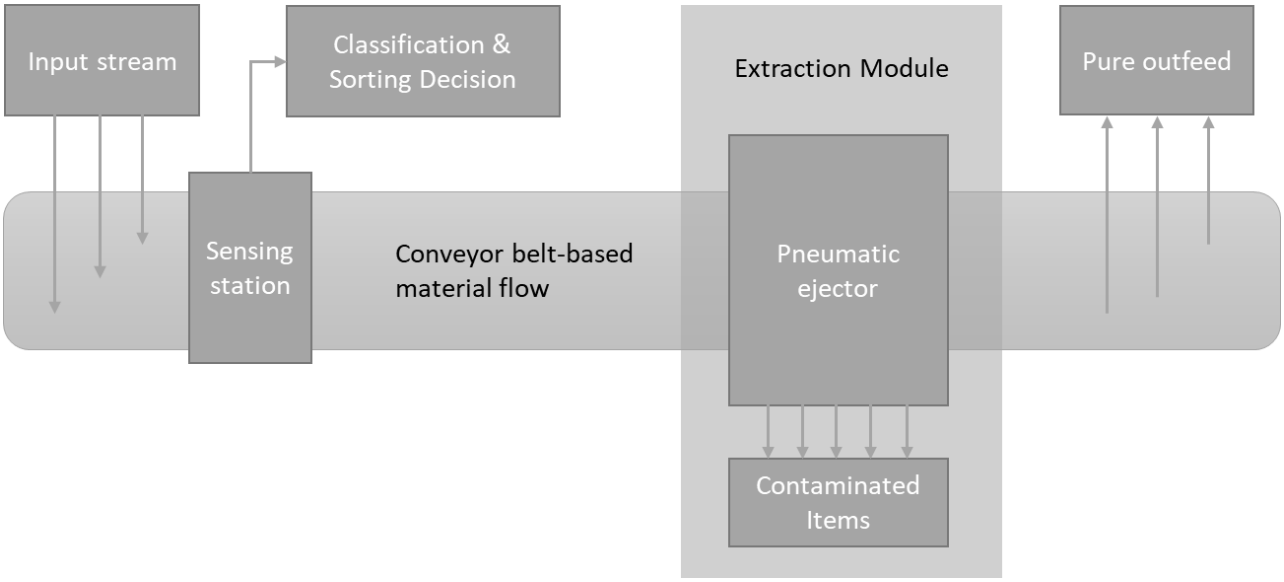


Figure 7: High-level concept of the metals sorting line, from conveyor feeding to sensing and pneumatic separation

5.2 Current system concept and implementation status

The current development activities are carried out at ICCS premises. The work is based on representative material samples provided by the host, which are used for laboratory experiments and sensing assessment. These samples support the evaluation of material separability and the preliminary definition of sorting logic before the system is transferred towards an industrial validation environment. The evaluated sensing techniques are described in the previous paragraph. The purpose of this comparison was to identify whether different sensing modalities provide useful and complementary information for distinguishing clean copper pieces from pieces with contaminants. The current assessment indicates that hyperspectral imaging provides a suitable basis for the intended sorting function, while the additional techniques tested did not appear to provide sufficient added benefit for the first implementation pathway.

The planned sorting system is expected to include a conveyor belt, a sensing station, and pneumatic separation module. The conveyor will transport metal pieces under the sensing station. The sensing system will assess the material characteristics of each item or region of interest. Based on the classification decision, the actuation module will activate and redirect selected pieces away from the main conveyor path. The use of air nozzles is considered appropriate for the current concept because it allows fast and contactless separation. Since metal pieces are heavier than textile or plastic items, the nozzle configuration requires higher air flow and sufficient actuation force. The required nozzle hardware is available, and the separation principle has been validated for the purposes of the current TRL5 scope. Further tuning will be required during the next development phase, especially when moving towards the final conveyor configuration and representative throughput conditions. A technical site visit has also been performed to assess the potential integration location within the Partner's facilities. This activity supports the transition from laboratory testing to deployment-oriented design. It also allows the consortium to account for practical constraints, such as available space, material flow, safety requirements, maintenance access, and compatibility with existing operations. Table 14 summarizes the current implementation status of the metals sorting line.

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Table 14: Current implementation status of the metals sorting line

Module / activity	Current status	Role in the metals sorting line
Relevant material samples	Available and used in ICCS laboratory experiments.	Support sample-based sensing and separability assessment
Spectral-based imaging	Tested and selected as the main sensing route	Supports identification of target and non-target copper pieces
X-Ray-based imaging	Evaluated during laboratory trials	Assessed as a complementary sensing option
Conveyor-based sorting concept	Defined and validated for current scope.	Provides the basis for future line development
Pneumatic separation module	Available and validated for current scope.	Redirects selected metal pieces from the conveyor
Site integration assessment	Performed through facility visit	Supports future installation planning

5.3 Validation activities and TRL5-readiness status

The validation activities performed so far focused on the feasibility of identifying and separating selected test specimens based on their material characteristics. The work was conducted at ICCS premises using samples provided by the collaborating Partner.

The first part of the validation concerned **sensing feasibility**. Different sensing technologies were tested on the available samples. The objective was to assess whether the techniques could support the distinction between pure copper pieces and pieces presenting contaminants or non-target characteristics. The comparative evaluation indicated that hyperspectral imaging is the most suitable sensing option for the first implementation of the sorting line, particularly when considering the balance between technical performance, integration simplicity, and compatibility with conveyor-based operation. The second part of the validation concerned the **separation principle**. The selected actuation approach is based on pneumatic ejection. The available setup was configured for higher-flow operation in order to account for the higher mass of metallic pieces compared with lighter waste fractions. The separation concept has been validated successfully for the current reporting scope. Further tests will be performed during system development to define the final sizing and configuration, air flow, timing, item spacing, and conveyor speed. The third part of the validation concerned **integration planning**. A technical site visit has been performed to assess where the sorter can be placed in the industrial facility. This activity is important because the sorting solution must be integrated within an existing industrial workflow. The future system must therefore be designed not only around sensing and separation performance, but also around safety, accessibility, maintainability, and compatibility with the available space and material handling logic.

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At the current stage, the metals sorting line is considered TRL5-ready for the **D4.2** scope. This assessment is based on the laboratory validation of the sensing route, the definition of the conveyor-based sorting architecture, the successful validation of the separation actuation principle, and the identification of the future integration context. The next maturity step will include the development of the integrated sorting line for deployment-oriented testing. Table 15 gives a more concise representation of the current validation and maturity status.

Table 15: TRL5-readiness assessment for the metals sorting line

Validation element	Current status	Evidence type	Assessment
Material samples	Provided by the line host and tested at ICCS.	Sample-based laboratory validation	TRL5-ready for current scope
Sensing techniques assessment	Tested and selected as main sensing method.	Laboratory sensing trials	TRL5-ready for current scope
Conveyor-based system concept	Defined	Public system architecture	TRL5-ready for current scope
Air-nozzle separation	Validated for current scope	Separation principle tests	TRL5-ready for current scope
Overall performance (classification and separation)	Consistent performance under continuous operation in short working cycles.	Aggregated preliminary results and laboratory tests	TRL5-ready for current scope

The current maturity assessment reflects the fact that the main technical principles have been evaluated and selected. The final industrial sorter is expected to be installed and tested under continuous facility operation during the next phase of the project, where the laboratory-validated approach will be translated into an integrated system suitable for testing in the line host's environment.

5.4 Open issues and next steps towards TRL6

The next phase of development will focus on the consolidation of the material definition, development of the integrated sorter, and preparation of the system for installation and testing at the hosting Partner's facilities.

1. The first of the next steps includes a common verification of the ground-truth categories in collaboration with the line host. This is important because the final sorting logic must reflect the practical material quality needs of the industrial Partner. The distinction between target and non-target pieces must be confirmed not only from a sensing perspective, but from the perspective of industrial relevance and downstream material handling as well.
2. The second next step comprises the development of the conveyor-based sorting system. This will include the detailed configuration of the conveyor, sensing station, actuation module, control logic, and collection areas. The system must be designed in a way that supports reliable material

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presentation, sufficient sensing time, reliable ejection timing, and practical handling of the sorted fractions.

3. The third step concerns the refinement of the separation module, as metal pieces are heavier than other material streams addressed in WP4, the actuation parameters will need to be tuned carefully and accordingly. Future tests will define the required air flow, nozzle positioning, item spacing, and conveyor speed. The goal will be to ensure reliable separation without creating unnecessary instability or safety risks.
4. The fourth next step concerns health and safety compliance. The final sorter will operate in an industrial environment and must therefore comply with relevant safety requirements. This will require collaboration to define safe installation conditions, guarding needs, access restrictions, emergency stops, maintenance procedures, and any additional site-specific safety provisions. Finally, in-situ testing will be required to move the system towards TRL6. This will validate the full sorting concept under more representative operating conditions, including actual material flow, environmental conditions, facility constraints, and interaction with existing processes.

Table 16: Next steps towards TRL6 for the metals sorting line

Next step	Purpose
Co-verify ground-truth categories with the line host	Confirm the final target and non-target material definitions
Finalize sensing configuration	Prepare the sensing station for integrated operation
Develop the conveyor-based sorting system	Translate the lab concept into an integrated sorter
Tune the separation module	Ensure reliable ejection of selected metal pieces
Confirm site integration requirements	Align the system with the selected facility location
Define health and safety measures	Ensure safe installation, operation, and maintenance
Install and test the sorter on-site.	Move from TRL5-ready status towards TRL6 validation

Overall, the metals sorting line has progressed from the conceptual design stage to a laboratory-validated sensing and separation approach. The current work supports TRL5 readiness for the **D4.2** scope, based on sample testing, sensing method selection, separation principle validation, and initial site integration planning. The next phase will focus on ground-truth consolidation, integrated sorter development, safety compliance, and preparation for in-situ validation.

6 Glass sorting line

6.1 Baseline and development

The glass sorting line addresses the automated inspection and sorting of glass bottles associated with the relevant THESEUS Partner. In **D4.1**, the glass sorting case was defined as a dedicated sorting line intended to support the identification, classification, and selective handling of bottles according to the requirements of

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the host use case. The developed concept was based on the integration of sensing, automated decision-making, and either robotic or automated handling within a conveyor belt-based process. The main objective of the glass sorting line is to sort bottles according to the requested bottle type and to detect apparent wear and damage where present. This is relevant because bottle quality and type identification directly affect the suitability of bottles for further use, rejection, or redirection within the existing industrial pipeline. The sorting task is thus not limited to material recognition, as all objects belong to the same broad material family. Instead, the challenge focuses on the reliable identification and distinction of bottle type, geometry, visible condition, and specific damage indicators.

In comparison with other sorting cases in **WP4**, the glass line presents particular technical constraints. The processed glass bottles are rigid objects and very well geometrically defined, but they are also fragile, brittle and reflective by nature. Their surface properties such as transparency, colour, labels, lighting conditions, and possible defects may detrimentally affect visual inspection. In addition, throughput requirements may become challenging if sorting is performed only through sequential robotic manipulation. For this reason, the current development considers both robotic handling and high-speed diversion mechanisms. The work carried out so far has focused on laboratory-based testing at ICCS premises, using relevant bottle samples. The available equipment includes robot arms, conveyor belts, and sensing units based on computer vision and hyperspectral imaging. However, the first validation activities indicated that hyperspectral imaging did not provide significant added value for the specific task of detecting damaged bottles. Optical inspection methods based on camera data are currently considered sufficient for the classification of bottle type and visible damage in the first implementation pathway.

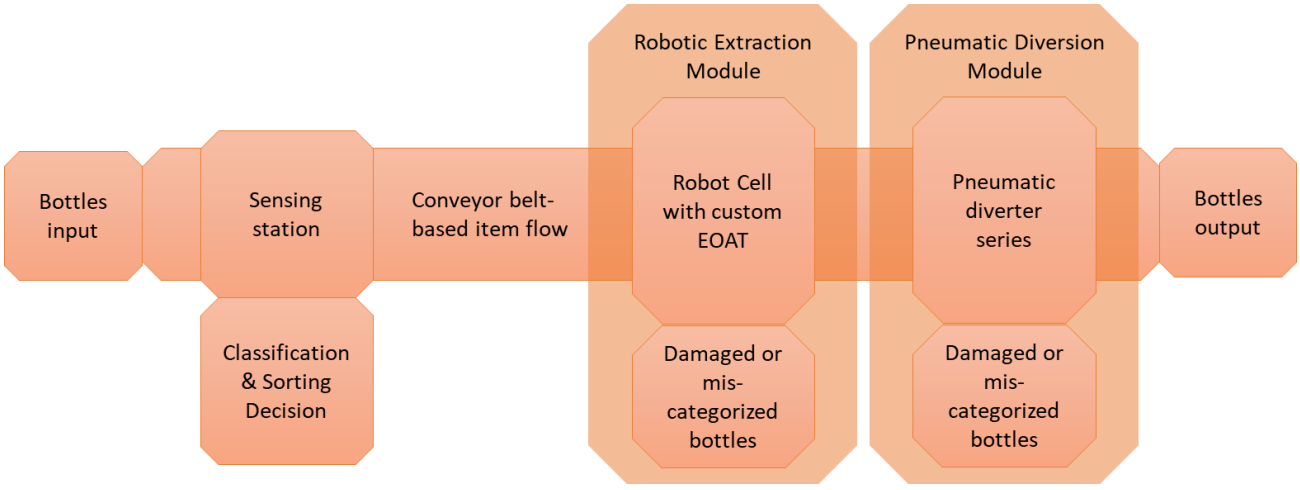


Figure 8: High-level concept of the glass bottle sorting line, from conveyor inspection to robotic handling or diversion

6.2 Current system concept and implementation status

The current development activities are carried out at ICCS premises. The laboratory infrastructure includes conveyor systems, robotic arms, sensing units, and relevant control components. Bottle samples provided by the line hosting Partner are used to validate the inspection and handling principles before the system is translated into an engineering design suitable for on-site integration.

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The sensing concept is based primarily on optical inspection. RGB-D cameras are used to support bottle detection, localization, and classification by type and visible condition. Hyperspectral imaging has also been considered and tested as part of the broader WP4 sensing capabilities. However, for the current glass sorting task, optical methods appear sufficient for the identification of damaged bottles and requested bottle types. Therefore, the current development direction prioritizes simpler and more practical sensing configurations for the first implementation.

The bottle handling concept is currently considering two complementary approaches. The first approach involves robotic manipulation using a specialized bottle gripping EOAT. An in-house designed gripper prototype is being considered in order to handle bottles in a stable and controlled manner. Initial gripping trials with bottles traversing on a moving conveyor have been performed successfully, confirming the feasibility of robotic interaction with the target objects. The second approach involves horizontal pneumatic diversion. This method is being considered as a way to increase throughput, since a single robot may limit the maximum sorting rate if every bottle must be individually grasped and relocated. A pneumatic diversion module is available at ICCS and has demonstrated high-cycle operation. Indicatively, the module is considered capable of operating in the range of 2500 cycles/min under laboratory conditions, subject to final confirmation and tuning. Further work is needed though to adapt this mechanism for gentle bottle handling, since glass items require controlled contact and acceleration to avoid breakage or instability.

Table 17: Current implementation status of the glass sorting line

Module / activity	Current status	Role in the glass sorting line
Bottle samples	Available and used at ICCS	Support bottle type and damage classification trials
Conveyor-based laboratory setup	Available at ICCS and tested	Supports controlled bottle transport during validation
RGB-D sensing	Available and used in trials	Supports bottle detection, localization, and optical classification
Hyperspectral imaging	Available and used in trials	Considered, but not prioritized for damage-based bottle sorting
Robotic manipulators	Available at ICCS and tested	Support bottle gripping and handling validation
Specialized EOAT	Prototype developed and tested	Intended to improve stable and controlled bottle manipulation
Pneumatic diversion module	Available at ICCS and tested	Candidate high-throughput sorting mechanism
On-site testing	Planned for next phase	Required to validate the system under relevant operating conditions

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6.3 Validation activities and TRL5-readiness status

The validation activities performed so far focused on the feasibility of bottle detection, bottle type classification, visible damage identification, and physical handling. These activities were performed in laboratory conditions at ICCS premises using bottle samples provided by the bottle recycling Partner.

The first part of the validation **concerned sensing and classification**. Camera-based inspection was used to classify bottles by requested type and to identify visible damage where present. The initial results indicate that optical methods are sufficient for the current sorting objectives. Hyperspectral imaging was assessed, but did not show a clear added benefit for the specific task of sorting damaged bottles. This finding supports a more practical and integration-oriented sensing approach for the first version of the line. The second part of the validation concerned **robotic handling**. Bottle gripping trials were performed using the available robotic infrastructure. The tests confirmed that passing bottles can be gripped successfully under controlled conditions. The use of a specialized bottle gripping EOAT remains under consideration in order to increase stability, reduce handling risk, and support more robust operation in future integrated tests. The third part concerned **high-throughput sorting alternatives**. A pneumatic diversion module available at ICCS has been considered as a complementary or alternative solution to robotic pick-and-place. This module can achieve high cycle rates and may be more suitable for cases where only redirection is required. However, since bottles are fragile, the mechanism must be tuned to ensure gentle handling. The final decision between robotic handling, pneumatic diversion, or a potential combined approach will depend on definitive throughput requirements, damage risk evaluation, geometry of the placement line, and industrial integration and safety constraints.

The current validation results indicate that the glass sorting line is TRL5-ready for the D4.2 scope. The main sensing principle has been assessed, the classification task has been demonstrated with bottle samples, robotic gripping has been tested successfully, and a high-throughput diversion option has been identified. The final engineering design and in-situ validation remain part of the next phase.

Table 18: TRL5-readiness assessment for the glass sorting line

Validation element	Current status	Evidence type	Assessment
Bottle detection and classification	Tested using optical sensing with consistent achieved accuracy	Camera-based laboratory trials	TRL5-ready for current scope
Robotic bottle handling	Tested successfully with moving bottles	Laboratory robotic handling trials	TRL5-ready for current scope
Pneumatic diversion	Available and assessed as high-throughput option	Laboratory module assessment	Partially validated

Based on the above, the glass sorting line is considered TRL5-ready for the current reporting scope. The main inspection and handling principles have been validated under laboratory conditions, and the next steps are clearly identified for transition towards TRL6-oriented deployment.

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6.4 Open issues and next steps towards TRL6

The next development phase will focus on translating the laboratory-validated concept into an engineering design suitable for integration at the line host's premises. This will require the final definition of the sorting architecture, including conveyor configuration, sensing position, lighting, actuation mechanism, collection paths, safety provisions, and interfaces with the existing process. A key open issue is the final selection of the actuation equipment and definitive tuning of the sorting actions. Whereas robotic handling offers flexibility and controlled placement, it may limit throughput if used as the only sorting mechanism. High speed pneumatic diversion can support higher cycle rates, but requires precise tuning to avoid bottle breakage, excessive impact, or unstable motion. A combined approach could also be considered, where the optical inspection provides the classification decision and the sorting action is selected based on the required category, throughput, and estimated handling risk.

The sensing configuration must also be finalized. The current experimentation suggests that optical inspection is sufficient for bottle type and damage-related classification. However, the final setup must be validated under the lighting, background, conveyor, and bottle presentation conditions that are expected at the factory floor. Particular attention will be required for bottle surface reflections and transparency, label variability, surface defects, partial occlusions, and, in certain corner cases, bottle orientation. Further validation will be needed with a larger and more diverse set of bottle samples. While the current samples support TRL5 validation, in-situ testing will be required to assess real process variability. This will include bottle spacing, line speed, lighting variation, encountered contamination, label differences, and the whole spectrum of damage types encountered during operation of the sorting line. Health and safety considerations will also be important in this case as well. The final system will operate in an industrial environment and must be compatible with personnel access, maintenance requirements, emergency stop provisions, guarding, pneumatic safety, glass breakage risk, and cleaning procedures. These issues will be addressed during the engineering design and integration planning phase. Table 19 sums up the main next steps towards TRL6.

Table 19: Next steps towards TRL6 for the glass sorting line

Next step	Purpose
Finalize the engineering design of the sorting line	Translate the laboratory concept into an integration-ready system
Confirm the sensing configuration	Select the final camera, lighting, and inspection setup
Expand bottle sample validation	Improve robustness across bottle types, labels, and damage cases
Finalize bottle handling approach	Select between robotic gripping, pneumatic diversion, or combined sorting
Tune the pneumatic diversion module	Increase throughput while ensuring gentle bottle handling
Evaluate specialized bottle gripper design	Improve stability and reduce handling risk during robotic sorting
Define factory integration requirements	Align the system with the selected installation point and process constraints

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Define health and safety measures	Address personnel safety, pneumatic safety, and glass breakage risk
Install and test the system at the host's premises.	Move from TRL5-ready status towards TRL6 validation

Overall, the glass sorting line has progressed from the conceptual design stage to a laboratory-validated inspection and handling approach. The current evidence supports TRL5 readiness for the **D4.2** scope, based on bottle samples, optical classification trials, successful robotic gripping tests, and the assessment of high-throughput pneumatic diversion. The next phase will focus on engineering design, integration planning, gentle handling optimization, and in-situ testing.

7 Cross-line synthesis towards TRL6

7.1 Consolidated TRL5-readiness status

The developments reported in **D4.2** demonstrate the transition of the **WP4** sorting lines from the requirement and conceptual design phase reported in **D4.1** towards first validated TRL5-ready solutions. The work performed so far has focused on laboratory-scale and representative-environment validation of the key technical principles required for the sorting lines, including sensing, classification, actuation, handling, and preliminary system integration. Across the different sorting cases, the validation activities were adapted to the specific characteristics of each material stream. The **mixed urban waste and plastics sorting line** combines sorting and material recovery within a shared robotic platform. The **textile sorting line** focuses on PET-cotton blend identification and air-nozzle-based separation. The **metals sorting line** focuses on sensing-based separation of copper pieces from pieces with contaminants. The **glass sorting line** focuses on bottle type classification, damage detection, and controlled sorting or diversion. Although the lines differ in technical configuration, all cases have progressed beyond conceptual design. At the current stage, the main sorting principles have been defined and tested at a level sufficient to support continuation towards TRL6-oriented deployment activities. Full in-situ operation, final-speed testing, and long-duration industrial validation remain part of the next phase. Table 20 provides a concise summary of the validation conclusions and next steps towards TRL6.

Table 20: Consolidated TRL5-readiness status across WP4 sorting lines

Sorting line	Main technical focus	Current D4.2 status	Main remaining step towards TRL6
Mixed urban waste and plastics recovery platform	Shared robotic sorting platform with interchangeable EOATs for mixed waste and plastics recovery	**TRL5-ready for current scope**	Structural installation, sensing deployment, and in-situ robotic trials on site.
Textile sorting line	PET-cotton blend classification and pneumatic-based textile separation	**TRL5-ready for current scope**	Extended line procurement, multi-category ejection, and testing on site.
Metal scrap sorting line	Hyperspectral sensing and pneumatic separation of target copper fractions	**TRL5-ready for current scope**	Ground-truth confirmation, integrated sorter development, and deployment planning

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Glass bottle sorting line	Bottle type classification, damage detection, robotic gripping, and high-throughput diversion assessment.	**TRL5-ready for current scope**	Engineering design, handling approach finalization, and in-situ testing.

7.2 Common findings across the sorting lines

The validation work performed during the **D4.2** period highlights several common findings across the sorting lines.

1. First, material presentation remains a critical factor for reliable automated sorting. This is particularly evident in textile sorting, where garments must be singulated before sensing and separation. It is also relevant for mixed waste and plastics recovery, where clutter, overlapping items, and irregular geometries affect detection and grasping. For metals and glass, object spacing, orientation, and controlled movement on the conveyor are also important for accurate sensing and actuation.
2. Second, the combination of sensing and actuation must be adapted to each material stream. Hyperspectral imaging is highly relevant for certain composition-based sorting tasks, such as textiles and metals. However, it is not equally beneficial for all cases. In the glass sorting line, optical inspection appears sufficient for bottle type and visible damage detection. This confirms that the **WP4** approach should remain application-driven rather than sensor-driven.
3. Third, actuation strategy is one of the main differentiating factors between the sorting lines. Robotic gripping is suitable where flexibility and selective handling are required. Vacuum suction gripping is promising for plastics recovery, especially for bottles, bags, and packaging. Pneumatic ejection is suitable for textiles and potentially metals, provided that item mass, timing, and force are properly tuned. Pneumatic diversion may support higher throughput in glass sorting, but requires careful tuning to avoid instability or breakage.
4. Fourth, the transition from TRL5 to TRL6 will require a strong focus on industrial integration. The laboratory validation performed so far confirms the feasibility of the main technical principles, but each line must now be adapted to its intended host environment. This includes mechanical integration, safety provisions, environmental robustness, operator access, collection areas, maintenance, and compatibility with existing workflows.

Finally, the work confirms the value of modular sorting architectures. In several cases, the same core platform or logic can support multiple scenarios. This is especially clear in the shared mixed urban waste and plastics case, where **T4.2** and **T4.4** share the same robotic platform while using different end-effectors and sorting targets. A similar logic applies to the textile line, where the validated pneumatic extraction module can be replicated for multiple sorting categories.

7.3 Pathway to TRL6

The next phase of **WP4** will focus on moving the sorting lines from TRL5-ready laboratory or representative validation towards TRL6-oriented deployment in the relevant host environments. This transition will require engineering design, integration planning, safety preparation, expanded validation, and in-situ testing.

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1. For the mixed urban waste and plastics sorting platform, the next steps concern the installation of the robotic cell above the conveyor, the development of the required structural support, the adaptation of deposition bins, and the deployment of the data collection system. This system will initially support stream mapping and will later support the sensing function of the integrated robotic sorter. Additional validation will focus on object clutter, higher-speed operation, protection of the robot and EOATs in the facility environment, and safety measures for personnel.
2. For the textile sorting line, the next steps concern the expansion from the ICCS laboratory setup to an extended sorting line at the line host's premises. This will include further validation of PET-cotton blend classification, development of the two-stage singulation mechanism, replication of the pneumatic separation module for multiple sorting categories, and integration of category-based collection containers. Further testing with more diverse textile items will be required to improve robustness before and during in-situ validation.
3. For the metals sorting line, the next steps concern the consolidation of the target and non-target material definitions in collaboration with the sorting line host. The sensing configuration will be finalized and integrated into a conveyor-based sorter with pneumatic separation. Further work will focus on tuning the separation module, confirming site integration requirements, and addressing health and safety compliance before deployment-oriented testing.
4. For the glass sorting line, the next steps concern the engineering design of the line to be integrated at the hosting industrial facility. The sensing setup will be finalized based on optical inspection, while the final sorting action will be selected between robotic handling, pneumatic diversion, or a combined approach. Further validation will focus on gentle bottle handling, larger sample variability, throughput, and safety issues related to pneumatic operation and possible glass breakage.

Table 21 below summarizes the main next steps towards TRL6 in a more structured form.

Table 21: Consolidated next steps towards TRL6

Sorting line	Main next steps
Mixed urban waste and plastics recovery	Build and install robot support structure. Finalize deposition bins. Install data collection system. Validate cluttered objects. Transfer plastics suction scenario to the shared platform. Increase experimental speed. Define safety and equipment protection measures. Start in-situ trials.
Textile sorting	Complete additional laboratory validation. Finalize public-safe metrics. Develop two-stage singulation. Procure and install extended sorting line. Replicate nozzle modules. Expand testing beyond ground-truth specimens. Integrate category-based containers. Start in-situ trials.
Metal scrap sorting	Confirm ground-truth categories with the host Partner. Finalize hyperspectral configuration. Develop conveyor-based sorter. Tune higher-flow air-nozzle separation. Confirm site integration requirements. Define health and safety measures. Perform expanded sample validation. Prepare in-situ testing.
Glass bottle sorting	Finalize engineering design. Confirm camera and lighting setup. Expand bottle sample validation. Select final sorting action. Tune pneumatic diversion for gentle handling. Evaluate specialized bottle gripper. Define integration and safety requirements. Start in-situ testing.

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7.4 Conclusions

D4.2 reports the first implementation and validation update of the THESEUS sorting lines developed within **WP4**. Building directly on the requirements, constraints, and conceptual designs established in the previously submitted deliverable **D4.1**, the report documents the transition from requirement-driven design towards the initial validated technical configurations for the sorting of 5 distinct material streams, namely mixed urban waste, plastics, textiles, metal scrap, and glass bottles. The reported work therefore represents an important intermediate stage in the progression of the THESEUS sorting technologies, positioning them appropriately for the next phase of deployment-oriented development.

The work carried out during this reporting period confirms that the main technical directions selected in **D4.1** remain valid and technically relevant. Across the different sorting cases, the core sensing, classification, handling, and separation principles have been implemented or tested at laboratory or representative level. The **shared mixed urban waste** and **plastics** platform has demonstrated the feasibility of robotic extraction with interchangeable end-effectors. The **textile sorting line** has demonstrated the basic sensing-to-ejection logic for PET-cotton blend separation. The **metals sorting line** has identified a suitable sensing route and validated the pneumatic separation principle for selected copper-containing fractions. The glass sorting line has confirmed the relevance of optical inspection for bottle type and damage-related classification, while also assessing both robotic handling and pneumatic diversion as possible sorting actions.

A key outcome of **D4.2** is that the sorting solutions have progressed beyond conceptual design without being presented as final industrial systems though. This distinction is important for the interpretation of the deliverable. The evidence reported here supports TRL5 readiness for the current scope, meaning that the main technological principles have been tested sufficiently to justify continuation towards TRL6-oriented development. At the same time, full in-situ validation, factory-conditions operation, long-duration trials, and final industrial integration remain part of the subsequent project phase.

The validation activities also provided useful technical feedback that will be utilized for the next development cycle. Across the sorting lines, the most important cross-cutting issue is material presentation. Reliable automated sorting depends not only on the selected sensing technology, but also on the way material is introduced, spaced, oriented, detected, and made available for actuation. This is especially evident for textiles, where singulation of the stream remains essential, and for mixed waste, where clutter and overlapping objects must be addressed. Similar considerations also apply to metals and glass, where object spacing, conveyor motion, and interaction with the actuation mechanism influence the reliability of the sorting action.

Another important conclusion concerns the need to remain application-driven in the selection of sensing and actuation technologies. The work showed that advanced sensing modalities are essential when they address a specific material distinction, but they do not automatically provide additional benefit in every case. For example, hyperspectral imaging remains relevant for

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composition-related sorting tasks, while optical inspection is currently sufficient for the glass bottle case. Similarly, the actuation approach must be selected according to the object type, throughput needs, fragility, mass, and required sorting action. Robotic gripping, vacuum suction-based extraction, pneumatic ejection, and pneumatic diversion each present different advantages and limitations depending on the stream.

The work also highlights that the next phase of the project is expected to be strongly integration-oriented. The main challenge will no longer be only whether each technical principle works in isolation, but whether the complete line can operate reliably in the intended host environment. This will require engineering design, mechanical integration, safety planning, protection of equipment, connection with existing workflows, expanded validation with representative material streams, and in-situ testing. These activities will form the basis of the transition from TRL5-ready status to actual TRL6 readiness.

Overall, **D4.2** confirms that the **WP4** sorting lines have reached an appropriate level of maturity for a public V1 deliverable at this stage of the project. The results provide a credible technical basis for the continuation of the developments and define a clear pathway towards TRL6. The following **WP4** deliverable in this sequence, **D4.3**, will build on the present work by focusing on deployment-oriented integration, relevant-environment testing, and the further validation of the sorting lines under conditions identical to their intended operation.

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