WOOD2WOOD

A Wood-to-Wood Cascade Upcycling Valorisation Approach

» Deliverable 5.3

Adaptive glass and wood sorting systems (version 1)

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PROJECT INFORMATION

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0.2	29/04/2025	Konstantinos Vasios	ToC & Draft Material - WP5
0.3	04/06/2025	Konstantinos Vasios	Draft submission for review
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REVISION AND HISTORY CHART

Dissemination Level		
PU	Public	X
RE	Restricted to a group specified by the consortium	
CO	Confidential, only for members of the consortium (including the European Commission Services)	

Legal Disclaimer

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GLOSSARY OF ACRONYMS

Acronym	Extended Definition
CA	Consortium Agreement
Cobot	Collaborative Robot
D	Deliverable
DoA	Description of Action
EC	European Commission
FTIR	Fourier Transform Infrared Spectroscopy
MFC	Melamine Faced Chipboard
PC	Project Coordinator
TL	Task Leader
W2W	Wood2Wood
WP	Work Package
WPL	Work Package Leaders
XR	Extended Reality
XRF	X-Ray fluorescence
XRT	X-Ray Transmission

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EXECUTIVE SUMMARY

i. Wood2Wood Deliverable 5.3, "Adaptive Glass and Wood Sorting Systems (Version 1)," describes the technical design of the system aiming to sort wood and glass waste streams, as they arise from construction demolition waste (CDW). The present document contains the detailed definitions of the design and integration of the perception/sensor apparatuses, such as RGB-D imaging, hyperspectral imaging (HSI), X-ray transmission (XRT) and X-ray fluorescence (XRF) as well as human-robot collaboration modules to allow for a highly effective and efficient operation.

ii. At the centre of the present document lies the analysis and definition of the wood classification system, which categorizes waste into five distinct classes: Clean, Non-Hazardous I, Non-Hazardous II, Hazardous I, and Hazardous II. This categorization arises a result of chemical and physical properties of the handled materials, which are then purposefully exploited as they pass through the multi-sensor arrays and robotic distinct modules for a clean separation.

iii. The main intro module following the shredder, with the HSI,RGB,XRT perception module and the ABB double gripper module will be responsible for the glass/metal separation as well as feeding the collaborative robot line with clean/non-hazardous with metals module (see D5.4) The "remaining wood with other contaminants" stream will be then fed to the consequent HSI, RGB with the two FANUC Delta robots for separation into the hazardous/non-hazardous and clean wood categories. The last module with the RGB, XRF and the air nozzles will lastly make a hazardous wood separation into two classes. This design allows for seamless integration, dynamic routing and real-time adaptability.

iv. The deliverable contains a sound technical analysis and rational on the glass/wood classification streams based on a thorough sample off-line analysis in combination with the current state-of-the-art in perception and mechanical separation for CDW sorting, outlining and implementation roadmap for stakeholders and policymakers. This approach aims in setting new benchmarks for circular economy and the wood/glass waste sorting sectors.

1. INTRODUCTION

1.1. PROJECT INTRO

The Wood2Wood project, as a Horizon Europe initiative, aims to develop an end-to-end framework for cascade valorisation of wood and glass waste as contained in construction demolition and furniture sectors waste. As a combined effort of a consortium of research institutions and industry partners it is aiming to address the need for circular solutions as an effort to reduce the reliance on new material extraction from natural resources. WP5 and the “Adaptive glass and wood sorting system” lies at the core of this effort with the development of an end-to-end solution, from waste-to-sorted-material-classes, integrating advanced perception and sensing capabilities, multi-robot, multi-grasping, high-speed robotic aggregates in combination with human-robot collaboration schemes in order to maximize precision and overall system reliability, safety and throughput.

For the on-the-fly and real-time material characterization and the required spatial reasoning for optimal robotic grasping we rely on the state-of-the-art perception systems, including RGB-D cameras and sensors such as hyperspectral imaging, X-ray fluorescence (XRF) and X-ray transmission (XRT). The system’s modular architecture includes advanced mechanical actuation based on high-speed multi-delta robot aggregates as well as a collaborative robot station enhanced with extended reality (XR) interface. This pipeline can address the complex waste streams, that can include metal, chemical and composite material contaminants and embeddings. This approach is driven by the corresponding Deliverable D4.3 “Recycled Wood Cascade Valorisation Framework” which defines a harmonized wood classification scheme, based on contamination criteria and it also aligns with the necessary corresponding European Standards for traceable and valuable upscaling material flows.

The key differentiator that distinguishes this line of work with previous similar effort lies primarily on the combination of the precision that characterizes the XRF and the XRT sensors for a real-time and on-the-fly material identification and contaminant detection in combination with the multi robot high speed multi-gripper aggregates.

1.2. Purpose of the Deliverable

The intended purpose of the current deliverable is to describe the analytical technical framework of the overall end-to-end wood/glass adaptive sorting system as a result of the coordinated efforts during the Month 8 to Month 18 of the project and specifically for the Tasks 5.3 "Adaptive glass sorting system based on recycling thresholds" and 5.4 "Adaptive wood sorting system based on cascade valorisation thresholds".

More specifically during the period between Month 8 and Month 18 the analytical progress was tracked and documented for all Tasks T5.3-4 and has been communicated with the all the WP5 Task Leaders during the scheduled monthly meetings as such:

Table 1: T5.3-4 Monthly Progress

Month	T5.3-4 Progress
8	• ICCS internal roadmap definition for WP5. • Literature review initiation.
9	• Sorter robotic solution draft with focus on gripper technology for potential handling of forceful manipulation for wood/glass separation from CDW. • Potential solutions with regards to MRC as well as MR specifications have been discussed based on concrete use cases.
10	• Wood/Glass sorting system architecture first 3D design draft based on GA definitions. • Robotic system definition for optimal flow. • Literature Review & Evaluation of Grasping Pose Prediction Technologies for optimal grasping in clutter and unknown objects/geometries.
11	• Completion of the first sorter architecture design. Output -- > 3D CADModel • Completion of literature review on grasping pose prediction.

	• Draft of a clear robot grasping prediction technology roadmap with with a running prototype (in simulation).
12	• Potential for a first real-world experimental setup for the development of robotic perception-grasping pipeline. • Preparation for EuroXR demo for the W2W project.
13	• Requirements definition based on WP4 deliverable - reshaping based on deliverables of WP4 and Task 4.3 for the overall sorter design. (Wood classes, hyperspectral imaging etc). • Robot Grasping Prediction Baseline Pipeline Development with depth perception for wood/glass. • Samples supply (ELLAKTOR, Ecomaison-IRIS). • Literature review on grasping for sorting system - pose prediction.
14	• Requirements definition based on WP4 deliverable - reshaping based on deliverables of WP4 and Task 4.3 for the overall sorter design. (Wood classes, hyperspectral imaging etc). • Review & Evaluation of Vision-Grasping Robotic Pipelines for Sorting & Recycling.
15	• Requirements definition for sorter. • Evaluation of Grasping Pose Prediction Current state of the art. • Data samples by ELAKTOR to be received soon. • Data samples by Ecomaison (by IRIS) to be received soon. • Request for labelled wood samples to LERMAB (ongoing comms).
16	• Finalization of the sorter requirements definition. • Finalization of the sorter design based on the requirements definition. • D5.3 ToC. • Samples Received by LERMAB. Measurements undergoing.
17	• Sorter Design Final Design • Deliverable D5.3 submission

1.3. Intended Audience

The principal intended audience of this deliverable contains stakeholders heavily invested in the circular valorisation of wood and glass waste streams, such as operators and managers in the construction and wood processing (. furniture) industrial sectors. These stakeholders are directly benefiting from our wood sample analysis, the consequent functional requirements for the end-to-end sorting system as well as our detailed analysis and schematics of the sorter design, as described the sections bellow.

Policymakers that develop relevant regulations and standards are also directly affected by the impact of the current line of work, as the technical developments act as enablers, deflationary forces in the economy, and potential market disruptors.

Lastly critically affected intended audience are also the research community and industrial technology applicators as they benefit from the produced applied knowledge on relevant cutting-edge systems.

Overall, this document can serve all those that seek a reference to develop or adopt sustainable waste management solutions within the context of the broader European circular economy.

1.4. Structure of the Deliverable

i. **Chapter 1** introduces the document, including a general project overview, the purpose of the deliverable, and its intended audience.
ii. **Chapter 2** presents the adaptive glass and wood sorting systems developed for the W2W project, focusing on the technological principles and components guiding the classification and sorting processes.
iii. **Chapter 3** defines the wood waste classification framework, including the methodology and experimental results used to distinguish between various wood classes.
iv. **Chapter 4** describes the design and architecture of the W2W sorter, outlining its functional requirements and the main modules involved in the system.
v. **Chapter 5** details the methodology for defining Key Performance Indicators (KPIs) related to the pilot implementation of the adaptive sorting system and presents the KPIs selected.

vi. **Chapter 6** provides the conclusions of the deliverable and outlines directions for future work.

2. ADAPTIVE GLASS AND WOOD SORTING SYSTEMS FOR W2W

2.1. Wood Value Chain

The wood value chain within construction, demolition, and furniture sectors has historically followed a linear "harvest-manufacture-discard" model, generating 30-40% of global solid waste from C&D activities alone[1,2]. This paradigm is being reconfigured through W2W's cascade valorisation framework, which introduces four critical circularity nodes:

1. Waste stream identification at source (construction sites, urban hubs),
2. Pre-sorting optimization using AI-driven material recognition[3,4],
3. Contaminant-specific separation via multi-sensor arrays[5,6], and
4. Grade-matched redistribution to upcycling pathways[2,7].

Modern wood value chains face three systemic bottlenecks: heterogeneous material inputs (varying wood species, composite materials), chemical contamination (halogenated compounds, heavy metals), and infrastructural fragmentation between collection points and biorefineries[1,8]. W2W addresses these through tiered sorting architectures - robotic arms remove macroscopic contaminants (nails, fixtures)[3], while XRF/XRT systems detect subsurface pollutants like chromated copper arsenate at ≤25ppm thresholds[5,9]. The processed output feeds into a digital twin system that predicts optimal cascade paths (material reuse → biochemical extraction) based on LCA-driven quality thresholds[2,7].

[1] https://www.sciencedirect.com/science/article/abs/pii/S0956053X10005672
[2] https://www.wileyindustrynews.com/en/news/hyperspectral-imaging-recycling-industry
[3] https://openknowledge.fao.org/server/api/core/bitstreams/064b4271-1b21-4e82-9670-e32a8ef8c376/content
[4] https://rgsnordic.com/en/robotsortering/
[5] https://www.suibosorting.com/glass-sorting-machine/pioneering-the-future-of-glass-recycling-ai-and-robotics-in-glass-sorting
[6] https://recyclinginside.com/recycle-glass/picvisa-revolutionizes-glass-recycling-with-artificial-intelligence-in-ecoglass/
[7] https://www.unido.org/sites/default/files/2009-12/Global_wood_furniture_value_chain_0.pdf
[8] https://ec.europa.eu/newsroom/intpa/redirection/item/746775
[9] https://redwave.com/en/products/redwave-xrf

2.2. Wood-Glass characterization modules

2.2.1. State-of-the-art

Contemporary wood-glass characterization systems employ layered detection protocols to handle mixed waste complexities:

- **Multi-Spectral Contaminant Identification**

Hyperspectral imaging (900-1700nm SWIR range) enables non-destructive differentiation of wood types (hardwood vs. MDF) and surface treatments (varnished vs. painted)[10,11]. When combined with XRF elemental mapping, the system achieves 98% accuracy in detecting arsenic (As) and lead (Pb) concentrations below EU hazardous waste thresholds[5,**Σφάλμα! Δεν έχει οριστεί σελιδοδείκτης.**]. For glass streams, AI-powered VIS-NIR classifiers distinguish soda-lime from borosilicate variants while identifying ceramic inclusions through morphological analysis[12].

- **Adaptive Sorting Architectures**

W2W's sorting modules utilize three-stage material cascading:

1. Primary separation: Dual-energy XRT discriminates high-Z materials (metals) from organics, achieving 15t/h throughput with <5% false rejection rates[4,**Σφάλμα! Δεν έχει οριστεί σελιδοδείκτης.**].
2. Secondary refinement: Collaborative robots (cobots) with force-torque sensors extract assembled components from wood panels, reducing manual intervention by 40%[3,7].
3. Tertiary grading leverages conveyor-embedded NIR sensors (1200–2500 nm) to classify wood into distinct grades based on chemical properties such as lignin content and polymerization states. This approach is supported by multiple studies demonstrating that NIR spectroscopy, when combined with machine learning and chemometric analysis, can

[10] https://www.mssoptical.com/material-sorting-equipment/
[11] https://pure.unileoben.ac.at/files/5868698/AC16100787.pdf
[12] https://www.suibosorting.com/glass-sorting-machine/smart-glass-ai-how-next-gen-sorting-technology-is-revolutionizing-glass-recycling-economics

accurately classify waste wood into quality categories, enabling efficient valorisation and recycling[13,14].

Glass purification leverages sequential ejection systems - initial air knives remove >95% of non-glass particulates, followed by laser-induced breakdown spectroscopy (LIBS) for colour-sorting cullet into flint/amber/green fractions at 30t/h capacities[15]. Real-time purity feedback loops adjust ejection parameters when contamination levels exceed 2% mass fraction[12,16].

- **Digital Integration Frameworks**

A centralized IoT platform aggregates sensor data (moisture levels, contaminant profiles) to optimize three operational parameters: shredder RPM adjustments for target particle sizes (10-40mm), robotic gripper force settings based on material density, and dynamic rerouting of substandard batches to chemical treatment modules[2,7]. Machine learning models trained on 160,000 spectral signatures reduce misclassification errors by 32% compared to rule-based algorithms[11,15].

2.2.2. Methodological Approach

The methodological approach aims to bridge the project's requirements definitions with their respective key performance indicators, the currently applied industry best practices, the current state-of-the-art in research, in combination with actively advancing key research and applied areas, such as the perception/sensing and advanced robotic actuation.

Regarding the aforementioned industry applied best practices, we should note that a wide range of advanced sorting equipment is already available on the market for both wood and glass waste separation. Commercial solutions increasingly rely on modular sensor-based sorting lines, featuring technologies such as near-infrared (NIR) spectroscopy, hyperspectral imaging, X-ray transmission (XRT), and X-ray fluorescence (XRF) for material identification and contaminant detection. Leading suppliers like TOMRA and Van Dyk offer optical sorting systems with multi-sensor configurations and AI-driven recognition, which are widely used for separating wood from

[13] https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4655697
[14] https://open.library.ubc.ca/media/stream/pdf/24/1.0392877/4
[15] https://www.wood2wood-project.eu/wp-content/uploads/2024/11/WOOD2WOOD-brochure-with-bleed-marks.pdf
[16] https://www.magneticseparations.com/equipment/sensors/x-ray-xrf-sorting-system/

contaminants such as metals, plastics, and hazardous substances[17]. For glass, optical sorters and multi-stage cleaning systems—including air knives, eddy currents, and advanced optical classifiers—are standard in modern material recovery facilities (MRFs), ensuring efficient separation and high purity of output fractions[18,19].

Therefore, our approach begins with the definition of a harmonised wood classification framework, which establishes five distinct wood classes—Clean, Non-Hazardous I, Non-Hazardous II, Hazardous I, and Hazardous II—based on contamination levels and material quality, informed by European and national standards. This classification underpins the entire sorting process, providing clear criteria for material routing and valorisation. Following this, the methodology identifies and integrates advanced sensing technologies, such as RGB cameras, hyperspectral imaging (HSI), X-ray fluorescence (XRF), and X-ray transmission (XRT), to enable real-time, non-destructive identification and characterisation of wood and glass waste streams. These technologies are selected for their proven effectiveness in laboratory and pilot environments, as well as their scalability for industrial deployment.

Building on the wood class definitions and sensor integration, the methodology ultimately leads into the design and specification of modular sorter components, including the XRF with air nozzles for hazardous material ejection, the XRT line for density-based separation, the dual-delta main sorting line for high-throughput automated classification, and the human-robot collaboration module for handling complex assemblies. This modular approach allows for interoperability and rapid operational adaptations to varying streams. The system can be tuned and fine-tuned for dynamic routing in an off-line and on-line/real-time process optimisation.

[17] https://www.tomra.com/waste-metal-recycling/applications/waste-recycling/wood
[18] https://picvisa.com/optical-sorting/ecoglass/
[19] https://www.glassrecycles.org/best-practices-1/mrf

3. WOOD CLASSES DEFINITION

As described in the deliverable D4.2, one of the key objectives of the W2W project is to develop a harmonised EU-wide classification system for wood waste, based on quality criteria and recommended end uses.

By analysing existing national classification systems across EU Member States and prioritising the highest-value applications in line with the EU waste hierarchy, a potential harmonised classification scheme can be outlined see Fig. 2. This proposed scheme would categorise wood waste into five distinct classes – Clean, Non-Hazardous I, Non-Hazardous II, Hazardous I, and Hazardous II – each defined as follows:

1. **Clean**
   This category would include untreated or mechanically processed wood, as defined in German, Dutch, Finnish, and French classification systems. The preferred end use for wood in this class would be material reuse, consistent with practices in Germany, the Netherlands, and France.
2. **Non-Hazardous I**
   Based on criteria from the German and Finnish schemes; this class would comprise chemically treated wood that remains below threshold levels for hazardous organic compounds (HOCs) and heavy metals and is not coated with HOC-containing substances. Such wood would be appropriate for material reuse, in line with the German model.
3. **Non-Hazardous II**
   Also informed by the German and Finnish frameworks, this category would include chemically treated wood below the thresholds for HOCs and heavy metals, including wood coated with HOC-containing substances. Material reuse would be permitted if the coating is removed, following the German classification approach.
4. **Hazardous I**
   Drawing from the Dutch and German schemes, this class would consist of wood treated with chemicals exceeding the limits for HOCs and heavy metals or treated with polycyclic aromatic hydrocarbons (PAHs). Acceptable uses would include limited material recovery,

such as synthesis gas or activated carbon production, as well as energy recovery under emissions-controlled conditions.

5. **Hazardous II**

   This category would cover wood treated with PCBs or CC/CCA preservatives, based on German, Dutch, and Finnish schemes. PCB-treated wood should be disposed of through emissions-controlled incineration, preferably with energy recovery. In cases where CC/CCA-treated wood cannot be incinerated appropriately and no landfill ban applies landfilling would be the fallback disposal option.

Importantly, the suggested priority uses in this harmonised classification are not mandatory. Instead, they represent the most value-added applications for each class, supporting a flexible and opportunity-driven approach. This framework would allow for varied uses of waste wood, up to and including the suggested priority uses. It could be further reinforced through targeted restrictions, incentives, policy goals, and enabling measures to promote cascading use and adherence to the waste hierarchy—elements.

	Clean	Non-Hazardous I	Non-Hazardous II	Hazardous I	Hazardous II
Quality Criteria	Mechanically pro cessed	Chemically treated; **no HOCs in coating**; HOCs, heavy metals **below** thresholds	Chemically treated; HOCs in coating; HOCs, heavy metals below thresholds	Chemically treated; HOCs, heavy metal above thres holds; PAH treated	PCB, CC/ CCA treated
Priority Uses	Material recovery	Material recovery	Material recovery (coating removed)	Material recovery (limited); energy recovery	Disposal

- HOC: Halogenated Organic Compounds
- PAH: Polycyclic Aromatic Hydrocarbons
- PCB: Polychlorinated Biphenyls
- CCA: Chromated Copper Arsenate

Figure 1: Proposed Wood Classes Separation

Based on these above-mentioned classes, the consortium defined specific substances of interest that will be responsible for the wood sample classification. The next figure presents these specific substances and their types, the corresponding thresholds as they have been defined within the European Union, and more importantly, the sensing techniques that can be used for their detection.

Substance (e.g., HOC or Metal)	Specific Types	Hazard Classification	Threshold (ppm or mg/kg)	Comments/Notes
Halogenated Organic Compounds (HOCs)	Polychlorinated biphenyls (PCB) Pentachlorophenol (PCP) Polychlorinated dibenzo-p-dioxins (PCDD) Polychlorinated dibenzofurans (PCDF)	Hazardous	50 (EU) 100 (EU) 15 (EU) 15 (EU)	* Fourier Transform Infrared Spectroscopy (FTIR) - Rapid screening of halogenated compounds * Hyperspectral Imaging (HIS) - Pre-screening, followed by lab analysis (if possible)
Metals	As (arsenic) Cr (chromium) Hg (mercury) Cd (cadmium) Pb (lead)	Hazardous	25 (EPF) 25 (EPF) 25 (EPF) 50 (EPF) 90 (EPF)	* X-Ray Fluorescence (XRF)
PAHs (Polycyclic Aromatic Hydrocarbons)	Creosotes	Hazardous		* UV-Vis Spectroscopy * Raman Spectroscopy - Qualitative detection of PAHs
Other Potential Contaminants	Chlorine (Cl) Fluorine (F)	Hazardous	1000 (EPF) 100 (EPF)	* X-Ray Fluorescence (XRF)

Figure 2: Specific substances, and the corresponding sensing techniques for the wood samples classification

3.1. LABELLED SAMPLES ANALYSIS

To start the implementation of the classification of the wood samples, the consortium defined a few steps to proceed with. The first one is to exchange wood samples between the corresponding partners to align the measurement procedures and build common libraries. The second one is for ICCS and IRIS to collect external wood samples, measure, characterize and classify them using the same sensing techniques as before, to enrich the before mentioned libraries.

3.1.1. LERMAB Samples analysis

Regarding the first step, LERMAB has sent to ICCS two wood samples for evaluating the settings of the sensing modules that they use. In Figure 4, the corresponding results are being presented.

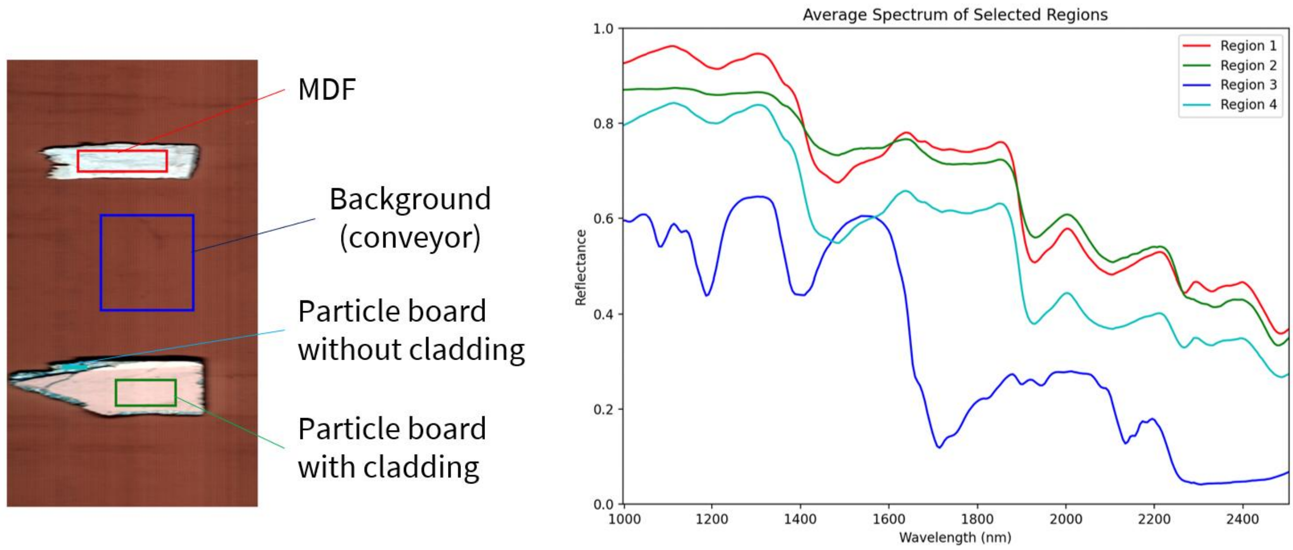

Figure 3: Measurement results of the wood samples that LERMAB shared with ICCS

In the left side of Figure 4, the two samples are depicted. The upper sample is the MDF, where the lower one, is the particle board. As presented, the MDF has one homogeneous top layer, labelled in red. The particle board, however, has two. The one with the cladding, presented in green, and the one where the cladding has been removed, labelled in cyan. In blue, the conveyor, which acts as the background, is presented. The spectra of the previously mentioned areas are shown on the right side of Figure 4. For the measurements, the SWIR camera from SPECIM has been used. The exposure time of the samples was 5 msec, and the scanning speed 120 Hz. The white and black reference was used as the methodology, and baseline correction as the corresponding technique, for the background noise.

Every material or class of materials has a unique chemical structure. As a result, the chemical bonds of each material have different energy levels. This means that when illuminated with the same band of light each material exhibits a characteristic spectral response that can be used for identification. Hyperspectral Imaging systems have the advantage of providing both spectral and spatial information about the image they capture. Due to this capabilities HSI has emerged as a very powerful tool for distinguishing different kind of materials in a CDW stream, thus able to separate wood from other types of waste from their IR “fingerprint”.

On the other hand, X- Ray Transmission (XRT) is another widely used technique which is based on the differential absorption of a high-energy beam of light through a molecular structure (an object). By measuring the number of photons that have passed through an object, we can extract information about the density and therefore the internal structure of the material, enabling the classification of different types of waste from wood and wood from wood with embedded metal objects.

The combination of these sensing technologies along with RGB cameras provides a comprehensive and efficient way of separating shredded waste.

Following the same characteristic spectrum principle, X-Ray Fluorescence spectroscopy (XRF) is particularly effective in the screening of wood samples based on the concentration of harmful metals and halogens, such as chlorine, above critical values, which could range from 700-1000 ppm e.g or chlorine, conditioned on the specific application and regional standards. This allows us to separate them into hazardous and non-hazardous wood waste. For these heavier elements especially, XRF instruments are even more sensitive given the fact that their electrons emit stronger, high-energy X-rays that are better detected and quantified.

3.1.2. Sample Labelling

We used different wood samples, common in this kind of streams, to employ in-lab offline techniques as in Fourier Transform Infrared Spectroscopy (FTIR range:1350–2500 nm) and Raman spectroscopy (785nm laser source). To initialize the analysis in various wood samples we chose several commonly found wood categories. Medium-density fibreboard (MDF), Melamine faced chipboard (MFC), orientated strand board (OSB), wooden planks with and without pigment coatings, and Pine wood were the five primary categories into which the samples under examination were divided. Untreated natural dried wood was also used as a reference sample for comparison (Fig. 1).

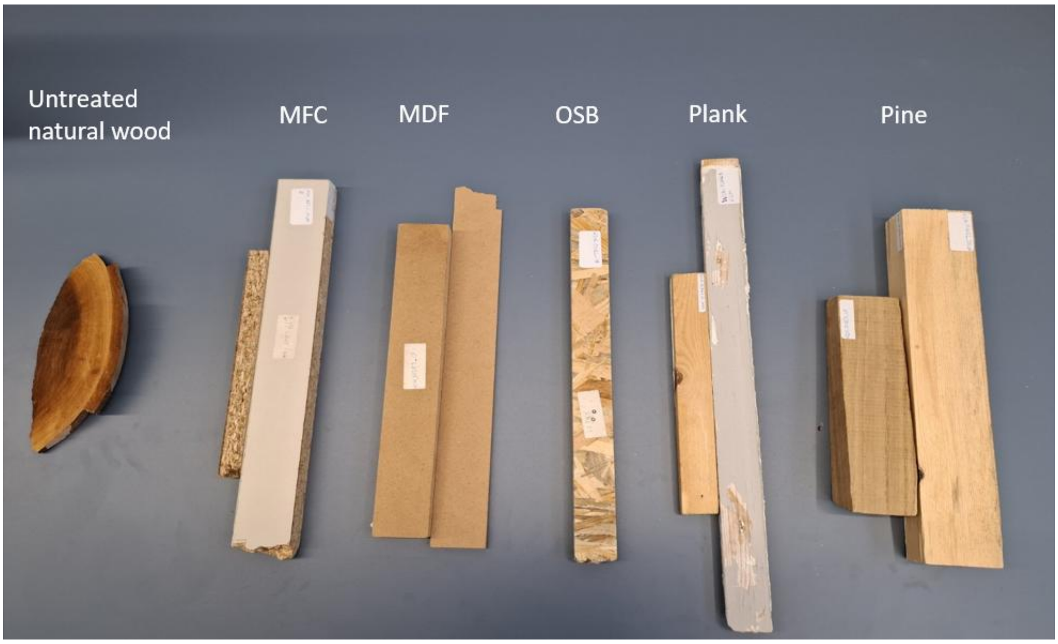

Figure 4: Labelled wood samples.

We obtained spectral information for both the coated surface and the hardwood substrate for every sample using FTIR and Raman yielding informing results.

The initial characterization of the samples showed us some spectral differences in woods that have been processed and clean woods. Functional chemical groups on sample surfaces were detected (FTIR); these groups may be a sign of different chemical treatments. Moreover, we can derive information about the different pigments in some processed samples. To identify more about the chemical processing and variations among the different pigments, Raman spectroscopy was also used.

3.1.3. Fourier Transform Infrared Spectroscopy (FTIR) Results

Wood Surfaces: Below (Figure 1) we present the average absorption spectrum of the hardwood side from all the samples of each category in FTIR.

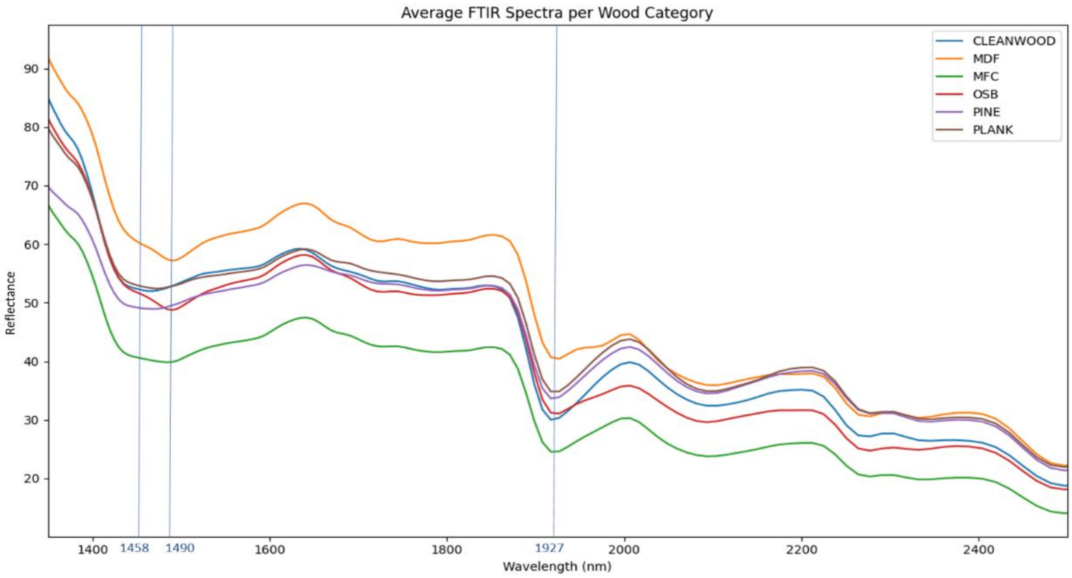

Figure 5: Average wood FTIR Reflectance

Results showed a clear absorption band centred around 1490 nm, in processed wood samples. This feature can be attributed to the first overtone and combination modes associated with amine (–NH_2) and amide (–CONHR) functional groups, appearing as N–H related combination bands in the spectrum. The presence of these nitrogen-containing functional groups could indicate that the wood surface has been chemically modified by treatments involving amine- or amide-based chemicals, residual processing agents, or adhesive contamination.

In contrast, untreated clean wood and pine (the latter appearing visually the least processed) lack the sharpness at 1490 and exhibit a broader absorbance in this region, with a local minimum at 1458 nm (blue and purple lines). This absorption is primarily due to C–H combination bands, which include the symmetric and asymmetric stretching modes of CH_2 and CH_3 groups present in cellulose, hemicellulose, and lignin—dominant molecular components found in all wood samples.

The spectrum of all the wood surfaces also showed absorption peaks at about 1927 nm, which is compatible with the overtone and combination vibrations of the carbonyl (C=O) and hydroxyl (O–H) functional groups. This area is typically linked to carboxylic acid (RCO_2H) groups, where substantial absorptions are produced close to 1900–1940 nm by the combination of the O–H bending and C=O stretching modes. The existence of surface-bound carboxylic acids, is possibly related to cellulose or introduced by oxidative weathering, may be indicated by the presence of absorption at 1927 nm.

Furthermore, overlapping absorptions in the 1200–950 cm^{-1} could indicate P–OH stretching and bending combinations pointing to the existence of residues or treatments based on phosphorus. These could include preservatives or fire retardants or naturally occurring phosphate esters.

Conclusion: We can observe that in the SWIR range of the IR spectrum we have regions of interest which can potentially guide us to distinguish treated from untreated wood by their infrared fingerprint.

- Coating/Pigment Surfaces: Below (Figure 2) the average absorption spectrum of the coating side of the samples in FTIR is presented.

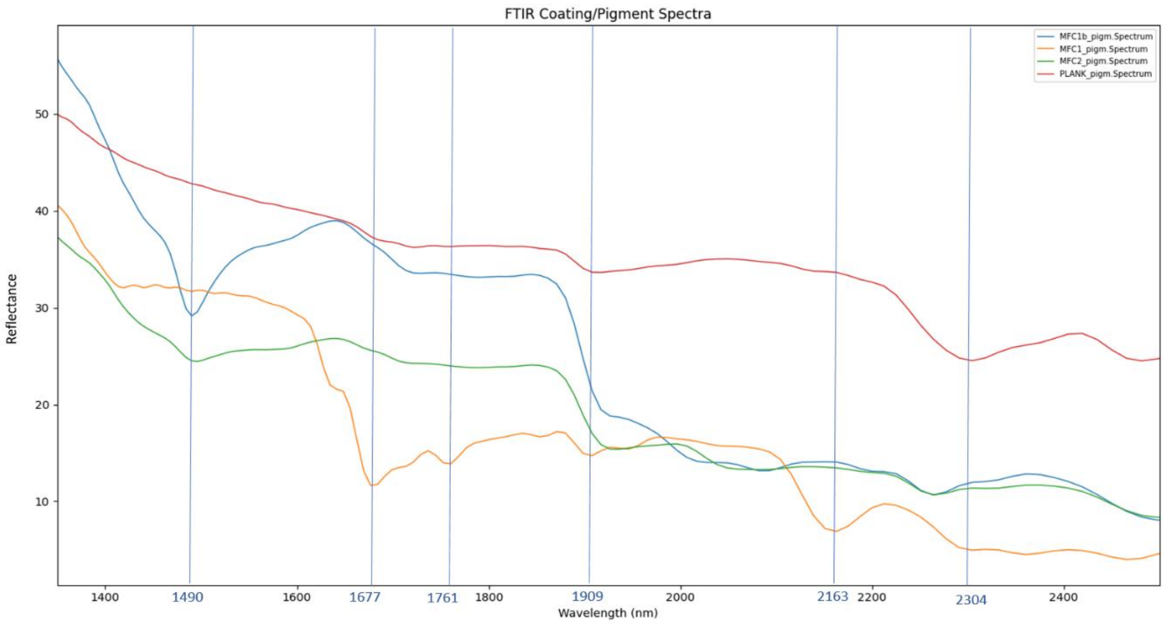

Figure 6: Coating Pigment FTIR Reflectance

We are discussing samples that contain pigment which are 'MFC' and 'Plank' samples. 'MFC1b' (blue line) represents the measurement from the top side of the sample and 'MFC1'(orange) corresponds to the lateral side of the sample. These sides have visual differences in their coatings despite being from the same sample, reproduced also in FTIR. 'MFC1' and 'MFC2' top sides look visually similar that is also to be reflected in the spectra.

Similarly, as before, for the top side of the 'MFC' samples we notice the same primary amine (RNH_2) or secondary amide (CONHR) absorption s at 1490 nm.

In the lateral side of 'MFC1' we find an absorption at 1677nm, indicating the presence of methylated compounds or aliphatic hydrocarbons in the matrix. The source of the band at 1761 nm could indicate C–H combination modes or possibly S–H group absorptions. The second case is less frequent unless sulphur-containing substances are used, like stabilisers or pigment dispersants.

Carboxylic acid (RCO_2H) functional groups, which show combination bands from O–H bending and C=O stretching, are prominent in the 'PLANK' and lateral side of 'MFC1' by the absorption at 1909 nm. Potentially organic acids, curing chemicals, or surface degradation byproducts are present.

There is an absorption at 2163 nm for 'MFC1' lateral side (C-C triple bonds (alkynes) or overtones of N-H combination bands). This can direct us to assume the possible addition of amine containing additives or cross-linker agents.

The dip at 2304 nm could be interpreted as C-H combination bands, frequently observed in polymer backbones, plasticisers, or HC-based carriers. These bands are usually linked to aliphatic chains or methylene/methyl stretching.

3.1.4. Pigment and wood surface comparison

We notice that for the two kinds of samples (MFC, Plank) between the coated sides and the plain wood sides we have two distinct spectral diagrams.

1. MFC

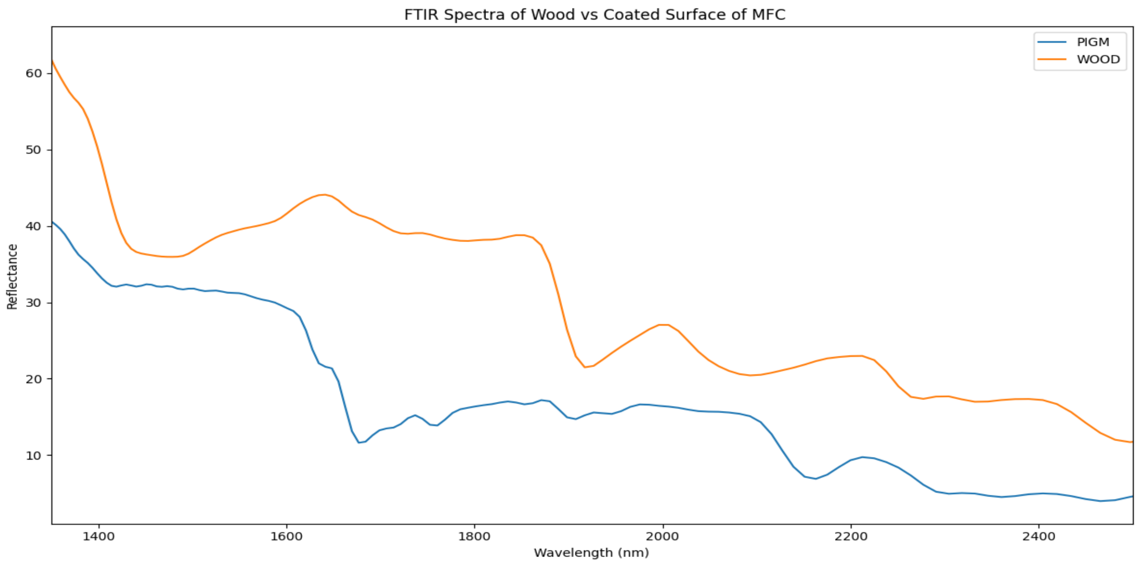

Figure 7: Comparison of MFC coated – wood Reflectance

We can observe noticeable differences between the two spectral lines. The pigment-coated lateral side of the MFC sample completely lacks the absorption feature at the 1453 -1490 nm region, observed on the hardwood surface. Additionally, the pigment side displays sharp dips at 1677 nm and 1761 nm, features that are absent in the hardwood spectrum. Finally, a distinct dip at 2163 nm is also observed exclusively on the pigment side. The potential causes for these spectral features have been discussed in the analysis above.

2. Plank

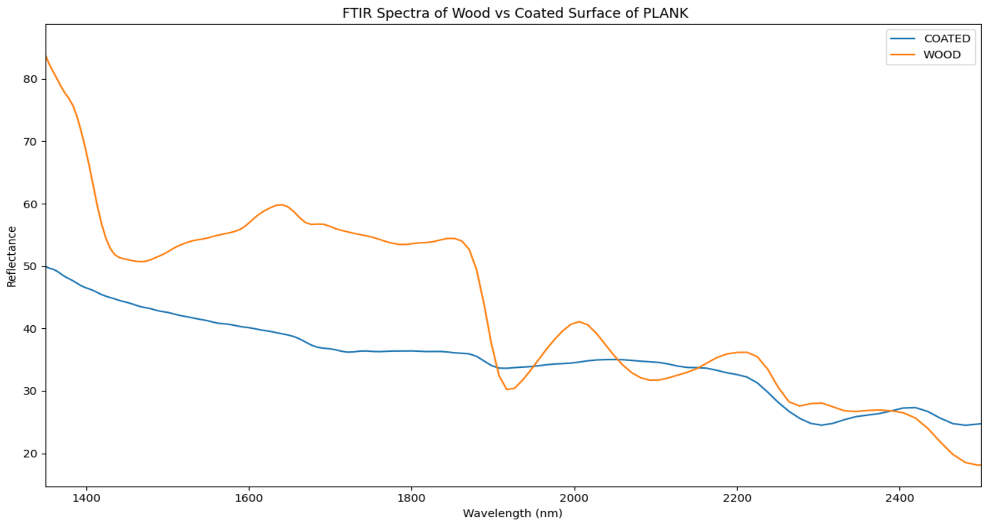

Figure 8: Comparison of Plank coated – wood Reflectance

Plank sides with pigment lack most of the features that were present when FTIR spectroscopy was performed at the hardwood side of these kind of samples. There was no response in the 1450 –1490 nm range and in the 1927nm which was common for all the wood surfaces. Completely missing from the wood spectral line, the dip at 2304nm provides another area of distinction for the different response the sides give to infrared. The potential causes for these spectral features have been discussed in the analysis above.

3.1.5. RAMAN Spectroscopy

'Plank' and 'MFC' coated sample surfaces seem to be differently treated thus Raman spectroscopy was also performed so that we can derive more information about the differences between their processing.

- Raman Spectrum for Plank Sample:

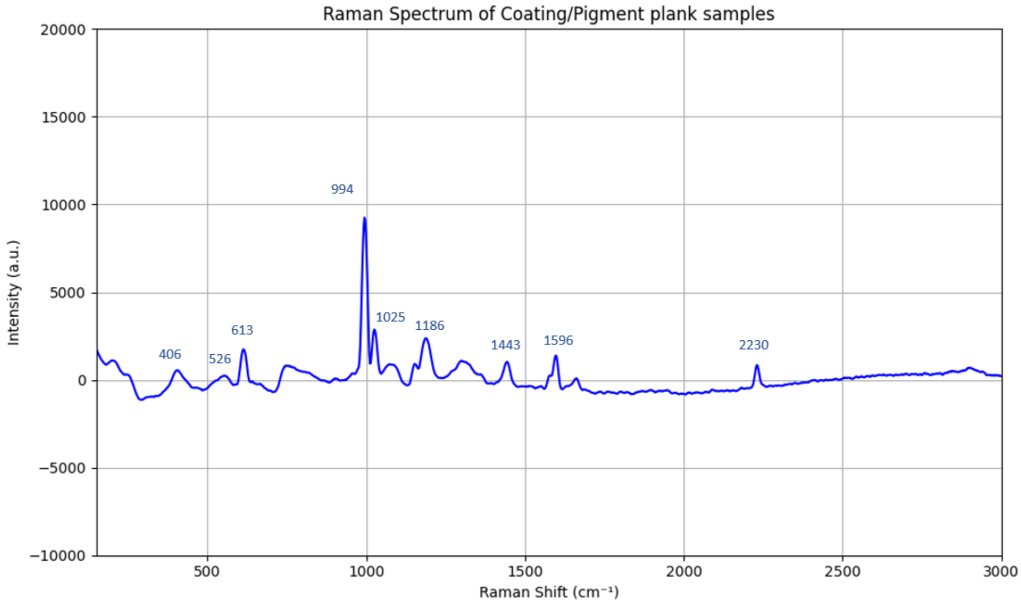

Figure 9: Plank coated side Raman spectrum

The first Raman peaks (observed are at 406, 526, 613 cm^{-1}) can be associated with the anatase phase (a tetragonal mineral consisting of titanium dioxide TiO_2). This is a phase commonly used in white pigments.

At 994 cm^{-1} the peak can be an indication of sulphate ions, which are also commonly found in paint formulas.

The existence of a peak at about 1027 cm^{-1} further indicates the presence of calcium compounds, which were probably added to improve the coating's whiteness.

N–H bending and C–N stretching modes are probably responsible for the noticeable Raman band at 1596 cm^{-1}, which is compatible with vibrations associated to amides.

Finally, at 2230 cm^{-1}, a sharp peak was detected at a range that commonly linked to C≡N (nitrile) stretching vibrations. This signal may also indicate the presence of isocyanate (–N=C=O) groups. The identification of these characteristics suggests the potential employment of either cyanate-containing additives, nitrile-functional polymers, or urethane-type resins, which can be present in cross-linking chemicals and coatings.

Raman Spectra for Coated Surfaces:

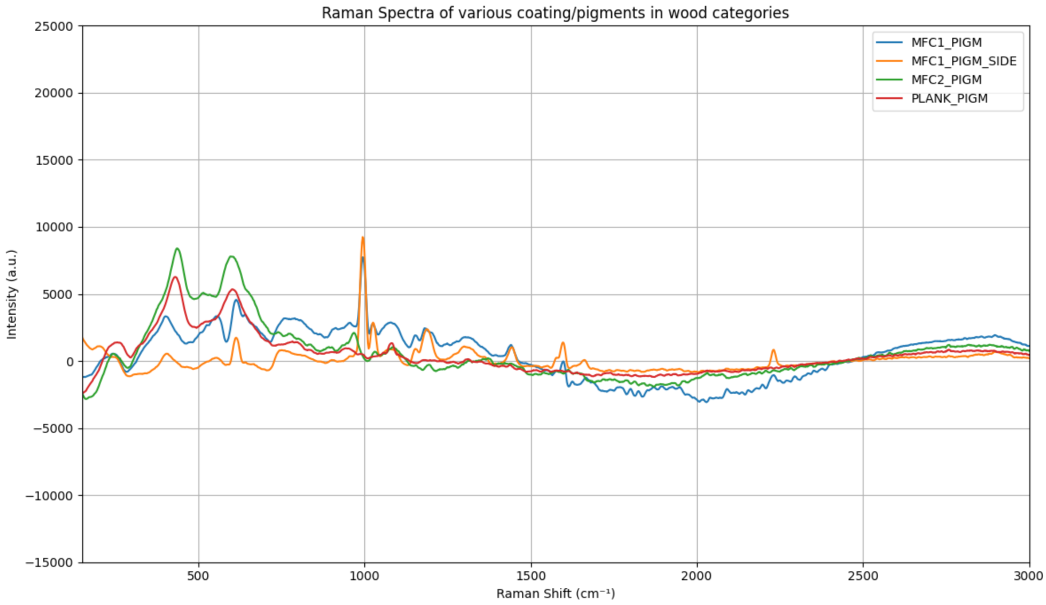

Figure 10: Coated samples Raman spectrum

The spectra of numerous coated/pigmented samples show comparable features in the composite spectral diagram above. This could be explained by the samples' generally light colouration and thus the existence of metal oxides such as TiO_2 or CaO, which is almost white, which reduces light absorption and makes similar functional groups more visible.

However, there are noticeable variances in certain absorption peaks, indicating that the coatings or pigments utilised have different chemical compositions and/or structural characteristics. The inclusion of various binding agents, additives, or surface-modifying substances may be the cause of these variations, as each directly affects the final spectral feature.

3.1.6. X-RAY FLUORESCENCE

Samples (coated)	Mg (mg/kg)	Al (mg/kg)	Si (mg/kg)	P (mg/kg)	S (mg/kg)	Cl (mg/kg)	K (mg/kg)	Ca (mg/kg)	Ti (mg/kg)	Cr (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	As (mg/kg)	Cd (mg/kg)	Hg (mg/kg)	Pb (mg/kg)
MFC1_PIGM_UP	3706.00	8646.00	6982.00	699.25	2270.50	<LOD	319.25	476.25	31602.75	<LOD	1129.00	13.75	<LOD	<LOD	<LOD	<LOD
PLANK01_PIGM	4150.00	10803.00	41456.00	266.00	<LOD	<LOD	1196.00	115157.00	80247.00	<LOD	1767.00	70.00	<LOD	<LOD	<LOD	<LOD
MFC1_PIGM_SIDE	3291.50	607.50	22182.50	919.50	1967.00	273.50	<LOD	3667.50	7658.00	<LOD	654.00	14.00	<LOD	<LOD	<LOD	<LOD
MFC1_PIGM_DOWN	<LOD	6551.00	5487.00	585.00	2414.00	<LOD	200.00	452.00	31601.00	<LOD	1356.00	15.00	<LOD	<LOD	<LOD	<LOD
MFC2_PIGM_UP	<LOD	10607.50	9479.50	838.50	1017.00	<LOD	286.50	624.00	18948.50	<LOD	1141.50	10.00	<LOD	<LOD	<LOD	<LOD
MFC2_PIGM_DOWN	<LOD	10130.50	8522.50	782.00	1094.50	<LOD	274.50	713.50	18875.50	<LOD	1150.50	11.50	<LOD	<LOD	<LOD	<LOD
MFC2_PIGM_SIDE	3364.50	2053.00	1327.00	88.00	998.50	<LOD	1395.00	3838.00	<LOD	188.00	497.50	10.50	<LOD	<LOD	<LOD	<LOD
PLANK2_PIGM	3693.00	11129.67	28466.33	303.67	1991.00	<LOD	876.00	88609.00	60325.33	<LOD	1413.33	47.33	<LOD	<LOD	<LOD	<LOD
PLANK4_PIGM	<LOD	7384.33	25137.00	303.00	8748.00	5012.33	809.67	98706.00	46457.67	<LOD	1493.33	22.67	<LOD	<LOD	<LOD	<LOD
MFC3_PIGM_UP	2802.00	17839.50	17342.00	277.50	1861.00	<LOD	528.50	567.00	9023.50	<LOD	8525.50	27.00	<LOD	<LOD	<LOD	4.00
MFC3_PIGM_SIDE	3218.00	1151.00	7534.00	112.00	2607.00	220.00	<LOD	3060.00	3768.00	143.00	819.00	11.00	<LOD	<LOD	<LOD	<LOD
MFC3_PIGM_DOWN	2812.00	14066.00	13901.00	266.50	2012.50	<LOD	469.50	584.50	9094.00	<LOD	8671.50	26.50	<LOD	<LOD	<LOD	<LOD
PLANK5_SIDE_PIGM	3963.00	11035.00	17457.00	274.00	3267.00	<LOD	753.00	71792.00	39988.00	<LOD	1161.50	13.00	<LOD	<LOD	<LOD	<LOD
PLANK6_PIGM	<LOD	10083.50	40467.50	327.00	1389.00	<LOD	1237.00	119905.50	74878.50	<LOD	2018.00	23.50	<LOD	<LOD	<LOD	<LOD
PLANK7_PIGM	4504.00	10389.00	41883.50	346.50	197.00	<LOD	1531.50	125055.50	73784.00	<LOD	1931.50	26.50	<LOD	<LOD	<LOD	<LOD
PLANK8_PIGM	<LOD	10356.50	41346.00	339.00	<LOD	<LOD	1232.50	123920.00	73578.00	<LOD	1979.50	29.50	<LOD	<LOD	<LOD	<LOD
PLANK9_PIGM	3690.33	11969.33	16037.33	358.00	1124.67	<LOD	1353.67	66086.67	33838.00	<LOD	1135.33	18.00	<LOD	<LOD	<LOD	<LOD
PLANK10_PIGM	3949.00	12204.33	12427.33	354.67	2799.67	<LOD	563.33	56997.67	26966.00	<LOD	936.00	15.67	<LOD	<LOD	<LOD	<LOD
PLANK11_PIGM_SIDE	4199.50	9366.67	30979.33	546.00	<LOD	<LOD	1071.67	128840.00	69725.00	<LOD	1772.67	23.33	<LOD	<LOD	<LOD	<LOD
PLANK12_PIGM_SIDE	<LOD	8906.67	35761.67	227.00	293.00	<LOD	1382.33	98025.33	73855.67	<LOD	1620.00	19.00	<LOD	<LOD	<LOD	<LOD
PLANK13_PIGM_SIDE	3881.00	10616.67	27301.33	257.00	397.00	<LOD	1142.67	88488.33	57701.33	<LOD	1503.33	18.00	<LOD	<LOD	<LOD	<LOD
PLANK14_PIGM_UP	4479.00	11406.00	31737.67	303.67	618.00	<LOD	1638.33	93745.00	47733.67	<LOD	1430.00	24.00	<LOD	<LOD	<LOD	<LOD
PLANK15_PIGM_UP	4054.50	11302.67	15480.00	355.67	1113.67	<LOD	838.50	63107.33	38271.67	<LOD	1101.00	17.33	<LOD	<LOD	<LOD	<LOD
PLANK16_PIGM_UP	4563.00	10152.33	32105.67	260.00	<LOD	<LOD	871.33	98279.33	64116.33	<LOD	1540.00	21.00	<LOD	<LOD	<LOD	<LOD
PLANK17_PIGM_UP	<LOD	9620.33	37898.33	273.00	938.50	1061.00	1290.00	118818.33	65737.33	<LOD	1910.33	29.67	<LOD	<LOD	<LOD	<LOD
PLANK18_PIGM_UP	4748.00	9011.67	24263.33	255.00	507.00	2957.00	656.00	92160.67	48010.00	<LOD	1295.33	20.33	<LOD	<LOD	<LOD	<LOD

Figure 11: XRF measurements of coated samples

Raman identified the presence of Ti and Ca oxides that are frequently used in white pigments. Those measurements were able to be validated by XRF measurements (Bruker S1 Titan) performed in the coated 'MFC' and 'Plank' samples, that yield high concentrations (in mg/kg) for those elements.

Another observation is that some coated samples can already be classified as potentially hazardous when we look at their respective Cl, Cr and Cu concentrations. The measurements highlighted in orange indicate levels above their thresholds set by EPF (European Panel Federation).

Conclusions:

- Distinct spectral patterns: FTIR and Raman measurements showed spectral differences between processed (coated or pigmented) wood samples and clean, untreated wood.
- Chemical treatments detectable: The presence of certain functional groups (such as amines, amides, carboxylic acids, and possibly phosphorus- or sulphur-based groups) was detected on the surfaces of processed woods. These features likely come from surface treatments, additives, adhesives, or pigments used in manufacturing.
- Pigments and coatings: Coated and pigmented surfaces had their own characteristic spectra, differentiating from the features seen in plain wood. For example, certain

absorption bands found in natural wood were missing or altered on the coated sides, while other new features appeared only in the pigments.

4. DESIGN OF W2W SORTER

4.1. FUNCTIONAL REQUIREMENTS

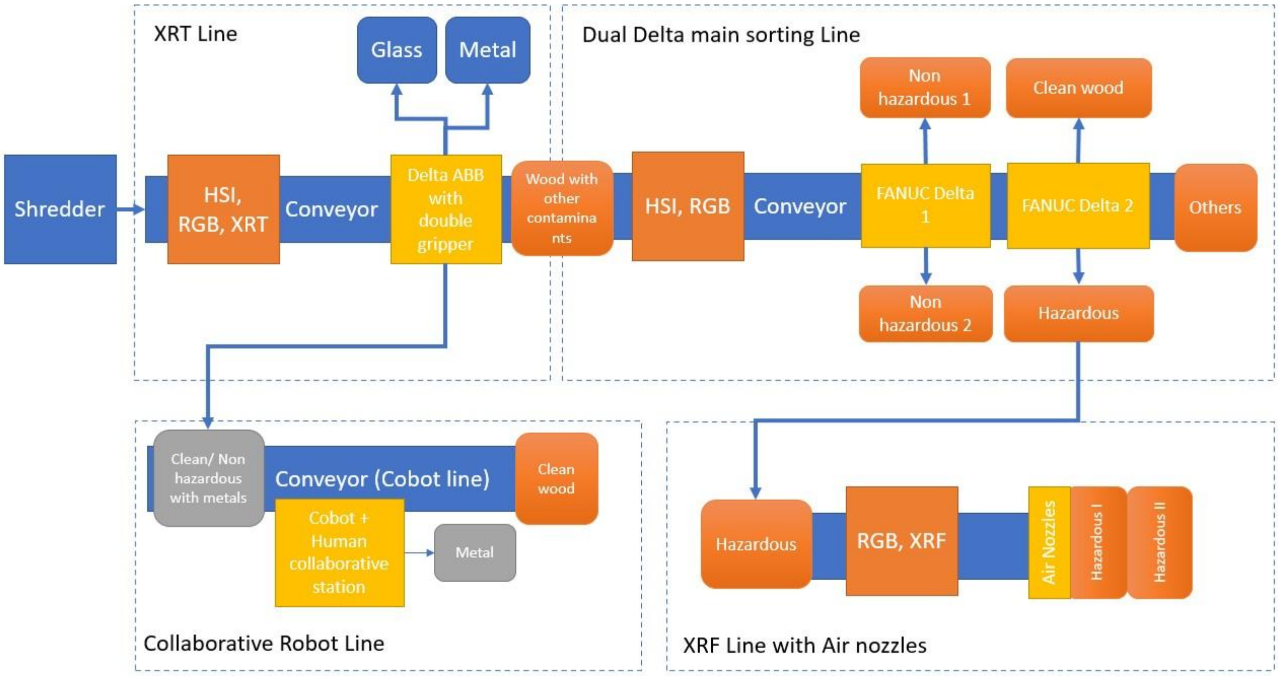

Figure 12: Wood/Glass Sorter Stream Flow Requirements

The adaptive sorting system must fulfil several key functional requirements to efficiently process mixed construction and demolition waste streams containing wood, glass, metals, and other materials. The system is designed to:

- Accept heterogeneous input material (wood, glass, metals, and others) after initial size reduction by a high-capacity shredder.
- Utilize a combination of advanced sensor technologies (RGB cameras, Hyperspectral Imaging (HSI), X-ray Transmission (XRT), and X-ray Fluorescence (XRF)) for real-time material identification and contaminant detection.
- Enable primary and secondary sorting via both automated (robotic arms, delta robots, cobots) and human-assisted modules, allowing for flexible handling of complex assemblies and contaminants.
- Support dynamic routing of materials through parallel and sequential sorting lines to maximize purity and recovery of target fractions.

- Integrate with downstream modules, such as air nozzles and specialized conveyors, to direct hazardous and non-hazardous materials to their appropriate destinations.
- Ensure traceability and quality control by maintaining digital records of sorting decisions and material flows for each batch.

4.1.1. Main Material Flow: From Input to Separated Outputs

The process begins with bulk mixed waste entering the system through a big shredder, which reduces the input to optimal particle sizes (see Deliverable D5.2). The shredded material, containing wood, glass, metals, and other debris, is then conveyed to the primary sorting stage equipped with RGB, HSI, and XRT sensors.

Final Outputs

- Clean Wood: Routed for high-value material recovery or upcycling.
- Metal: Sent for recycling.
- Glass: Directed to specialized glass recycling streams.
- Non-Hazardous Wood (I & II): Allocated for material or energy recovery, depending on contaminant levels.
- Hazardous Fractions: Managed according to safety and regulatory protocols, ensuring proper disposal or specialized treatment.

4.2. Sorter Architecture Overview

The overall design on functional requirements and the main modular architecture is presented in Figure 12.

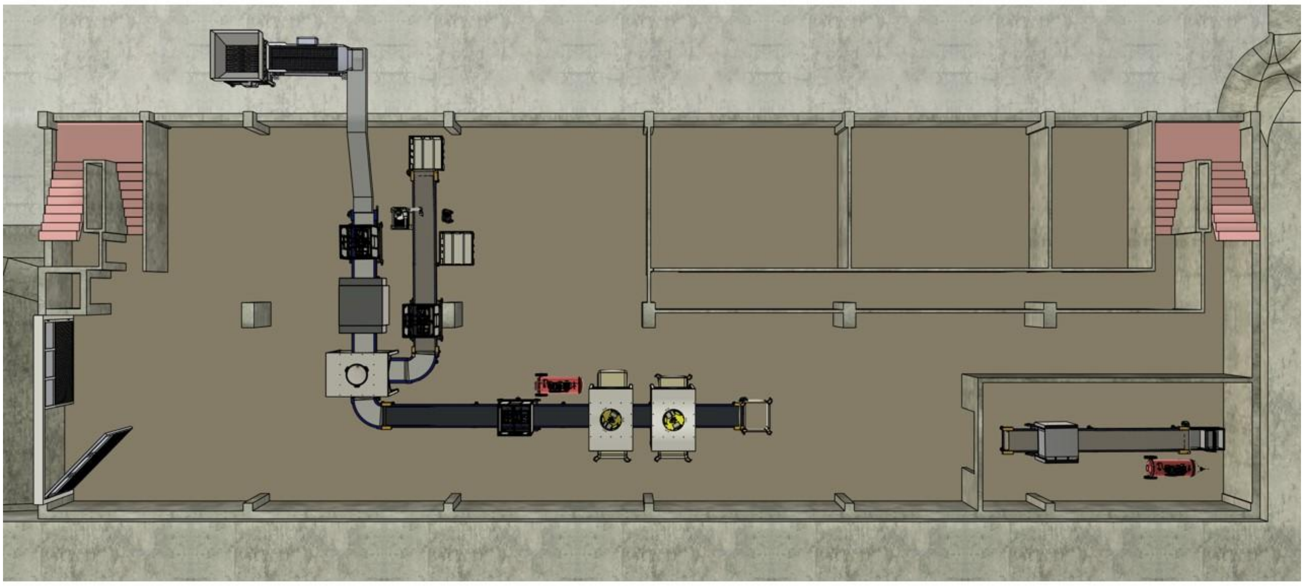

Figure 13: Wood/Glass Sorter Modules Overview 3 Top-View

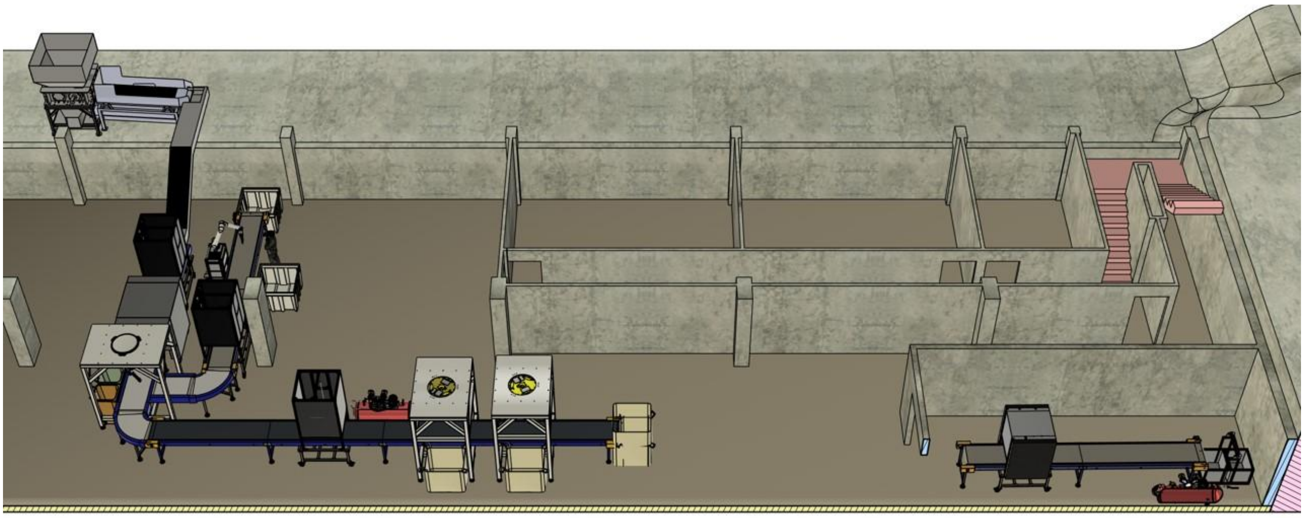

Figure 14: Wood/Glass Sorter Modules Overview 3D Top--Tilted-View

4.2.1. Main Material Flow: From Input to Separated Outputs

The process begins with bulk mixed waste entering the system through a big shredder, which reduces the input to manageable particle sizes. The shredded material, containing wood, glass, metals, and other debris, is then conveyed to the primary sorting stage equipped with RGB, HSI, and XRT sensors (see Figure 12 & Figure 13).

- **Primary Sorting**
  - Sensor Suite (RGB, HSI, XRT): The first conveyor uses these sensors to distinguish between clean/non-hazardous wood with metals, glass, and other fractions.
  - Delta Robots/ABB Delta Pickers: Identified fractions are picked and routed. Clean/non-hazardous wood with metals is separated from glass and pure metals.
- **Parallel Sorting Lines**
  - New Line A (Conveyor with XRT): Clean/non-hazardous wood with metals is further sorted. Collaborative human-robot (cobot) stations remove metals, producing clean wood and metal fractions.
  - New Line B (Cobot Line): Human and cobot teams work together to dismantle assemblies, ensuring the separation of clean wood from metallic components.
- **Existing Line Processing**

Contaminated Wood Flow: Material identified as wood with other contaminants is directed to a separate conveyor, where additional RGB and HSI sensors, along with delta robots, further classify it into:

  - Clean wood
  - Non-hazardous wood (Types I and II)
  - Other residuals

- **Hazardous Material Identification**
  - XRF Line: Materials suspected to be hazardous are routed through an XRF sensor line, where air nozzles sort them into:
  - Hazardous I
  - Hazardous II

- Other fractions

4.3. Modules Description

4.3.1. Shredding (Optimal shredding size)

The shredding stage, as defined in Task 5.2 under the leadership of IRIS, is a foundational step in the W2W sorting process, ensuring that incoming wood and glass waste streams are reduced to an optimal particle size for downstream sorting and sensor-based identification. The fundamental objective is to strike a balance between efficient material throughput and the production of fragments that are appropriately sized for accurate detection of contaminants and effective separation in subsequent modules. By standardizing the shredding process, the system enhances the exposure of surfaces for sensor analysis and minimizes the risk of misclassification or loss of valuable material. The chosen shredding parameters are designed to be adaptable to varying input materials and will be further detailed and validated in the dedicated deliverable D5.2, ensuring seamless integration with the overall adaptive sorting architecture and alignment with the cascade valorisation framework of the project.

4.3.2. XRF with Air Nozzles (Separate Hazardous I & Hazardous II)

Figure 15: XRF with Air Nozzles

The XRF with Air Nozzles module (see Figure 15) is designed to identify and separate hazardous wood fractions from the mixed waste stream, targeting contaminants such as heavy metals and chemically treated wood. This module is positioned downstream in the sorting process, following initial size reduction and pre-sorting, and is a critical step for ensuring that hazardous materials are efficiently diverted from recyclable and upcyclable streams.

Functional Principle

- **Detection**: As material is conveyed through the module, an X-ray fluorescence (XRF) sensor array rapidly scans each piece, analysing the emitted X-ray spectra to detect the presence of key hazardous elements (e.g., arsenic, chromium, copper, lead) associated with chemical wood treatments.
- **Classification**: The system compares detected elemental concentrations against configurable threshold values, classifying each item as either hazardous (e.g., CCA-treated wood) or non-hazardous, and further distinguishing between different hazard levels (Hazardous I, Hazardous II) as defined by project criteria and regulatory standards.
- **Separation**: Upon identification, the control system triggers a series of high-speed air nozzles aligned along the conveyor. These nozzles are capable of precisely ejecting targeted items from the main flow, directing them into designated output bins for hazardous fractions. The air ejection is dynamically adjusted based on the size, weight, and position of each detected item, minimizing the risk of cross-contamination.

Module Architecture

- **Conveyor System**: Ensures even material presentation and stable feed rate, which is essential for accurate detection and reliable diversion performance.
- **XRF Detection Chamber**: Mounted above the conveyor, this chamber houses the X-ray source and detector array, providing real-time, non-destructive elemental analysis of each passing item.
- **Air Nozzle Array**: Strategically positioned downstream of the detection point, these nozzles are controlled via a central logic unit that synchronizes ejection timing and pressure with the conveyor speed and material flow. The design allows for modular adjustment of nozzle positions and air pressure settings to accommodate different material sizes and densities.

- **Material Entry**: Pre-sorted wood and other materials enter the XRF line from upstream conveyors.
- **XRF Scanning**: As each item passes under the XRF sensor, its elemental composition is analysed in real time. While XRF measurements can be performed rapidly—often within a few seconds per item on industrial lines—the system is designed to accumulate sufficient signal for reliable detection of hazardous elements, even at low concentrations. This ensures accurate classification according to regulatory thresholds, while maintaining high throughput and minimizing processing delays.
- **Sorting Decision**: The system continuously evaluates the measured elemental concentrations against predefined hazardous thresholds. Items that exceed these thresholds are assigned to Hazardous I or Hazardous II categories, while non-hazardous materials proceed along the main conveyor path.
- **Air Ejection**: Corresponding air nozzles activate, diverting hazardous items into their respective output channels, while non-hazardous materials continue the main conveyor path.
- **Output Streams**: Sorted materials are collected in clearly separated bins or conveyors for further processing, safe disposal, or upcycling, as appropriate.

Key Features and Advantages

1. **High Sorting Efficiency**: Automated XRF with air nozzle systems have demonstrated strong performance in diverting hazardous wood, with high recovery rates for treated and untreated fractions in full-scale trials.
2. **Dynamic Adaptability**: The module allows for offline as well as real-time adjustments of detection thresholds and ejection parameters.
3. **Reduced Cross-Contamination**: Fast, targeted air ejection minimizes the risk of hazardous material mixing with clean fractions, supporting downstream quality and compliance.

Role in the Overall Sorting System

The XRF with Air Nozzles module serves as the final safeguard for hazardous material removal within the W2W sorter architecture, ensuring that only compliant, non-hazardous wood proceeds to valorisation or recycling, while hazardous streams are reliably isolated for appropriate handling.

4.3.3. XRT Line

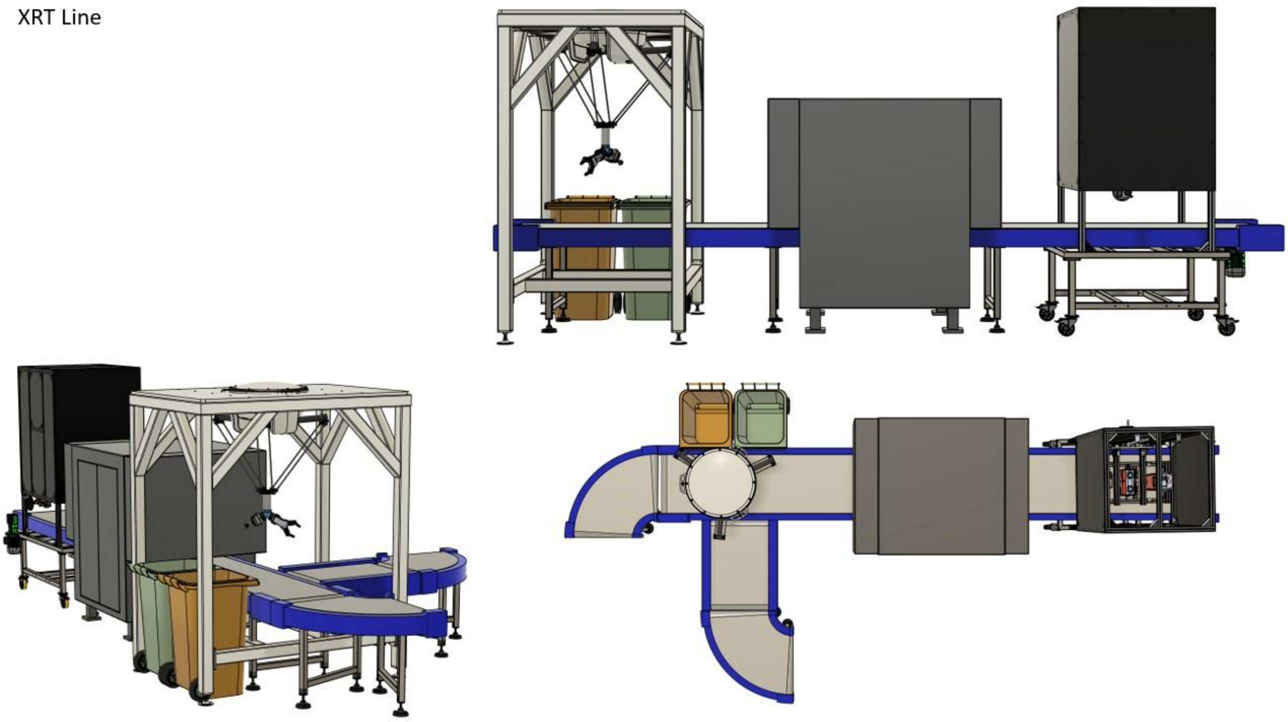

Figure 16: XRT Line

The XRT (X-ray Transmission) Line (see Figure 16) represents an integral component of the W2W adaptive sorting system, designed to perform primary separation of mixed material streams based on atomic density differentiation.

Technology Foundations

The proposed XRT module employs X-ray transmission technology positioned above a specialized conveyor system. This configuration enables the material type classification, through the analysis of its internal composition. It is important to note that this material composition analysis can occur regardless of the material surface conditions or contamination, Unlike surface scanning technologies.

The system utilizes a specialized X-ray source to generate a controlled beam that penetrates materials on the conveyor. Detection arrays positioned opposite the source capture transmission data, which is then analysed by advanced algorithms to distinguish between materials with different atomic densities. This approach allows the system to potentially differentiate between:

- Wood materials (low density organic matter)
- Metals (higher density materials)

- Glass and ceramics (intermediate density inorganic materials)
- Plastics and composites (variable density synthetic materials)

Material from the primary shredding process enters the XRT sorting line where it undergoes density-based characterization. The sorting algorithms are being designed to recognize specific material patterns and boundaries, enabling identification of complex assemblies such as wood with embedded nails, laminated materials, and overlapping objects.

The system architecture contemplates integration with downstream ejection mechanisms that could respond to detection signals to direct materials to appropriate streams. For clean/non-hazardous wood with metals, the materials would be directed to the dedicated cobot line for precise separation, while pure metals and glass could be routed to their respective recovery pathways.

Performance Considerations

The XRT module is being conceptualized to handle variable throughput rates based on material characteristics and desired separation precision. Key performance factors under consideration include:

- Material presentation optimization to reduce overlap and improve detection accuracy
- Algorithm refinement for recognizing complex material composites
- Integration capabilities with upstream and downstream sorting modules
- Adaptability to varying input stream characteristics

The XRT technology's ability to perform bulk density-based sorting makes it suitable as an early-stage separator in the modular W2W system, preparing material for more refined separation in subsequent stages of the sorting process.

4.3.4. Dual-Delta main sorting line

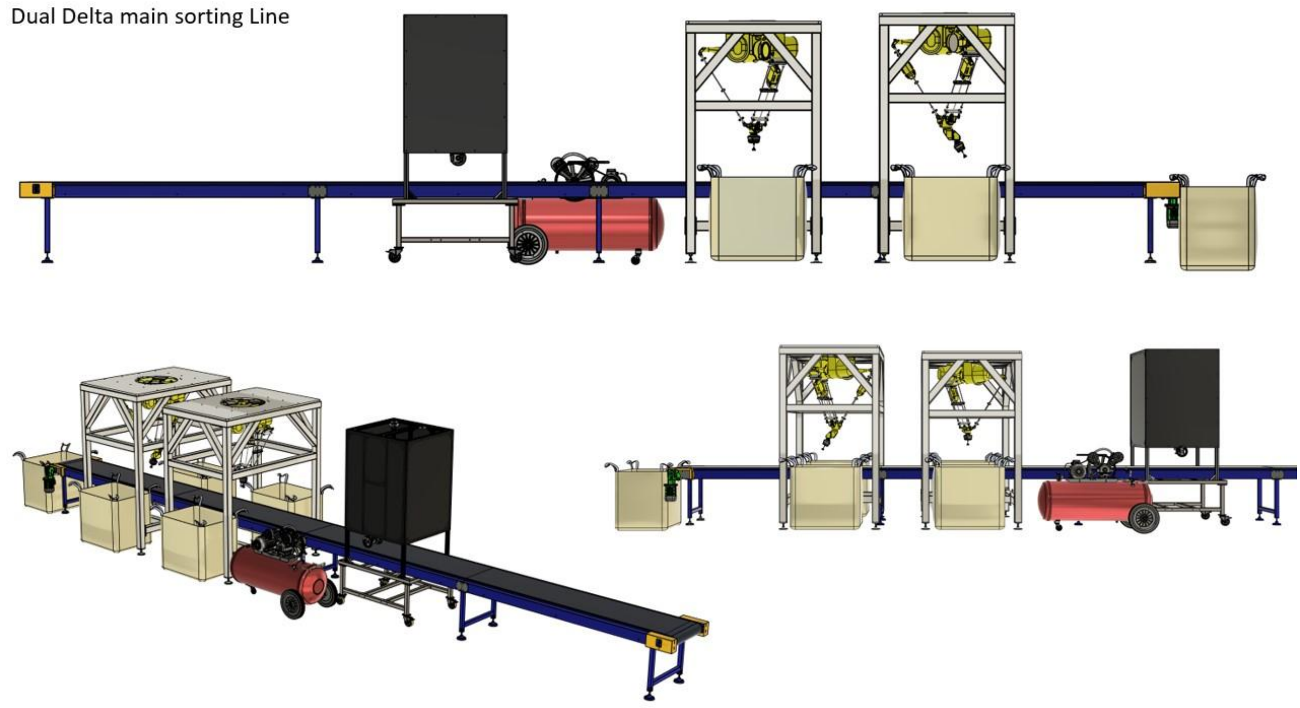

Figure 17: Dual-Delta main sorting line

The dual-delta main sorting line (see Figure 17) is a central module in the W2W adaptive sorting architecture, designed to efficiently classify and separate wood waste streams with varying contamination profiles. This module leverages two high-speed delta robots, working in tandem with multi-sensory input, to enable precise, automated sorting of complex material mixtures following initial shredding and pre-sorting.

It is important to note at this point that the high-speed throughput of the delta robots can be maintained regardless of the variability of the particle sizes that reach this stage of separation, due to the incorporation of the current-state-of-the-art in computer vision and robotics control and planning which allow optimal picking, even under variable and irregular object/samples geometries.

Functional Design

- **Material input**: The input to the dual-delta line consists primarily of wood fractions identified as containing mixed or uncertain contaminants, as well as residuals from upstream sorting steps. Material is evenly distributed on a conveyor to optimize sensor exposure and robotic reach.

- **Sensor Integration**: The conveyor is equipped with both RGB and HSI (hyperspectral imaging) sensors. This sensor setup provides critical material properties such as colour, surface properties and chemical properties that can be utilized for the detection of contaminants, such as coatings and adhesives.
- **Dual Delta Robot Configuration**: Two delta robots are utilized along the conveyor in a sequential order. Each robot is programmed to grasp specific material classes based on sensor data and the corresponding material information extracted:
    - Delta 1: Focuses on extracting clean wood and high-priority non-hazardous fractions, removing them from the main flow for direct recovery.
    - Delta 2: Handles secondary sorting, targeting non-hazardous wood with more complex contamination or ambiguous sensor readings, as well as isolating remaining residuals.

Sorting Logic:

The dual-robot setup with the two delta robots is preferred as an effective option for optimal material coverage in combination with a flexible, adaptable and reconfigurable path planning and with multiple available picking/grasping options for end-effector tools. The main sorting logic of these two robots dictates that the Delta 1 will be responsible for removing the most clearly identifiable and valuable material early in the process, with the subsequent Delta 2 performing finer discrimination among the remaining items.

Output Streams:

- The materials are sorted into three main output categories:
- Clean Wood: Suitable for high-value recovery or upcycling.
- Non-Hazardous I and II: Differentiated based on the degree and type of detected contaminants, aligned with project-specific valorisation pathways.
- Others: Residuals and ambiguous fractions, which may require further processing or be routed to appropriate disposal or treatment lines.

Key Features and Advantages

- **High Throughput and Flexibility**: The dual-delta configuration supports rapid, parallelized sorting, increasing overall system throughput and allowing for real-time adaptation to changing material compositions.

- **Precision and Consistency**: By combining advanced sensor data with robotic manipulation, the module achieves consistent classification accuracy, minimizing cross-contamination between output streams.
- **Modular Integration**: The dual-delta line is designed for seamless integration with both upstream (shredding, pre-sorting) and downstream (hazardous material identification, human-robot collaboration) modules, supporting a modular and scalable sorting system.

Role in the Sorting System

This module is a core component of the overall sorter design, as it acts as a bridge between initial material characterization and final contaminant isolation. By efficiently separating clean and non-hazardous wood from more problematic fractions, the dual-delta main sorting line enhances overall recovery rates and ensures that downstream processes can focus on targeted treatment of hazardous or complex materials, in line with the W2W cascade valorisation strategy.

4.3.5. Metal containing wood – Human-Robot collaboration module interface (Separate Metal & Clean-Wood)

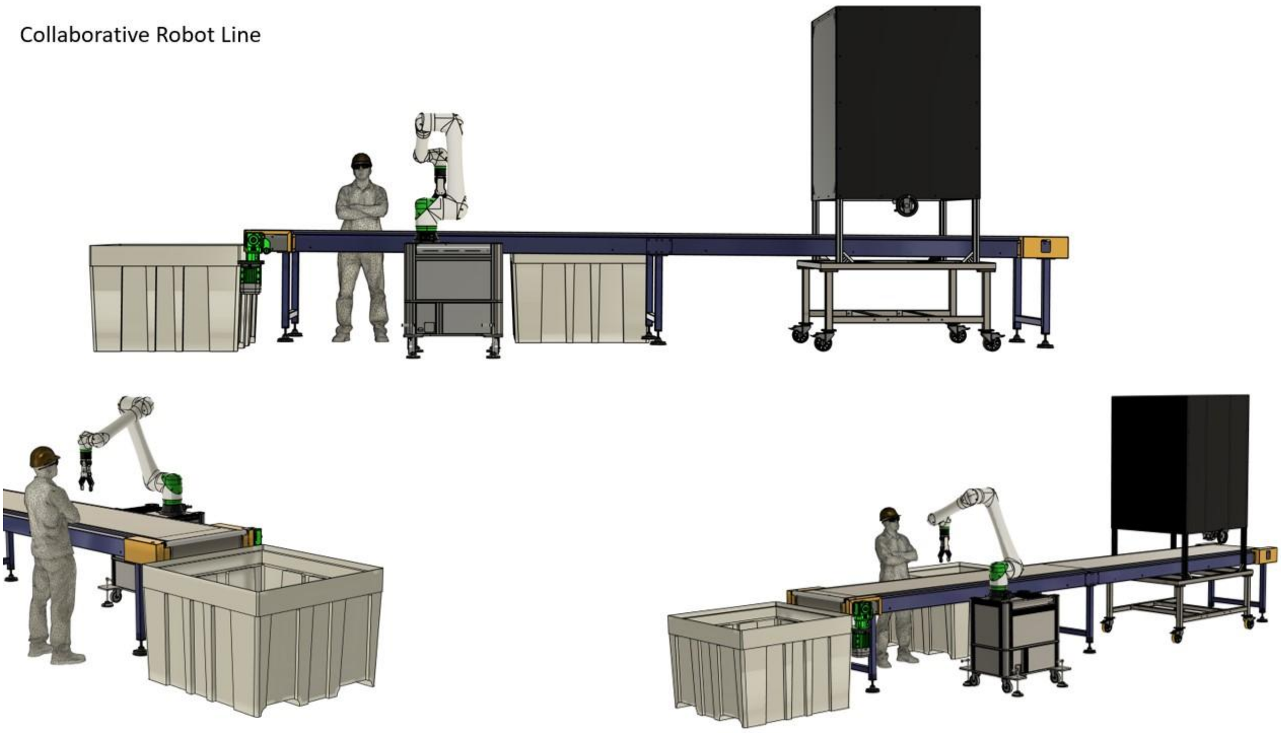

Figure 18: Human-Robot collaboration module

The Human-Robot Collaboration (HRC) module (see Figure 18) serves as a specialized processing station for wood components containing embedded or attached metal elements that conventional automated sorting cannot effectively handle. Positioned as a critical junction in the wood sorting pathway, this module receives material classified by the primary XRT detector as "Clean/Non-hazardous with metals" and employs a sophisticated collaboration between human workers and collaborative robots (cobots) to achieve precise separation. The station features a strategically designed workspace where incoming wood pieces with metal components are securely fixtured, allowing both the cobot and human operator to safely interact with the material simultaneously.

Technical Implementation and Process Flow

The module integrates advanced computer vision systems that first identify and localize metal elements (nails, screws, hinges, brackets) within the wood structure. This visual information is processed through an interactive Mixed Reality (MR) interface that creates a shared understanding between the human operator and the cobot. The system dynamically assigns tasks based on complexity - the cobot handles repetitive, precision-oriented extractions where force control is critical, while human operators address complex disassembly requiring dexterity and judgment. Task allocation is optimized in real-time to reduce operator fatigue while maximizing processing efficiency. Once disassembly is complete, the system performs quality verification through hyperspectral imaging to confirm complete metal removal before directing the now-clean wood to appropriate valorisation streams and segregating recovered metals for recycling.

The more specific and analytical aspects of these implementations are described in the deliverable D5.4.

5. KEY PERFORMANCE INDICATORS

5.1. METHODOLOGICAL CONSIDERATIONS

For the physical evaluation of our sorter design we rely heavily on the definitions provided in complete and comprehensive framework presented in the Wood2Wood Deliverable D5.4 and its Key Performance Indicators (KPIs). The provided KPIs ensure that the sorter design for wood/glass separation will deliver measurable, relevant and well aligned results according to the project's objectives.

The methodology can be described as follows:

- Document Analysis: A thorough review of the Grant Agreement and project documentation must be proceeded to address the technical and operational objectives of the sorting system with special focus on the classification accuracy, contaminated/hazardous material removal and overall system throughput.
- KPI Template Development: KPIs must follow a standardized template to induce accuracy and reliability. The templated KPIs entries should contain name, description, scope, formula, unit, range, and responsible owner (see Table 2).
- Validation and Finalization: KPIs must be reviewed by the assigned owners/stakeholders and should be accounted for the technical feasibility, overall effectiveness and soundness within the overall Wood2Wood valorisation context.

5.2. PILOT KPIS

The following KPIs are defined specifically for the adaptive glass and wood sorting system, reflecting its modular architecture and operational goals. These indicators are grouped into technical categories, as defined in D4.5, and are aligned with the project's broader sustainability and valorisation objectives.

Table 2: KPIs Definitions

KPI Name	Description	Scope/Module	Unit	Owner
Increase in efficiency of	Measures the accuracy of wood classification into	Main sorting line	%	ICCS

successful wood material classification	defined classes (e.g., Clean, Non-Hazardous I/II, Hazardous I/II)			
Improvement in latency of human-robot collaboration execution	Tracks the reduction in processing time for metal-containing wood streams	HRC module	%	ICCS
Sorting accuracy of hazardous material detection and ejection	Evaluates the effectiveness of the XRF with air nozzles module in detecting and removing hazardous wood	XRF with air nozzles module	%	ICCS
Throughput rate of the main sorting line	Measures the volume of material processed per unit time	Main sorting line	%	ICCS
Adaptability of sorting thresholds based on input stream	Assesses the system's ability to dynamically adjust classification criteria.	All modules	%	ICCS
System availability and reliability	Tracks uptime and operational reliability of the sorting system	All modules	%	ICCS

6. CONCLUSION AND FUTURE WORK

6.1. Conclusion

The present deliverable, "Adaptive Glass and Wood Sorting Systems (Version 1)," lays out a detailed technical and operational foundation for the transformation of wood and glass waste management within the W2W project. By integrating advanced sensor technologies—including RGB, hyperspectral imaging, X-ray transmission (XRT), and X-ray fluorescence (XRF)—alongside modular robotic and human-robot collaboration systems, the document establishes a flexible and adaptive sorting architecture capable of addressing the complex challenges posed by heterogeneous construction, demolition, and furniture waste streams. Main motivation for this approach is the classification efficiency, clean separation for being ultimately routed to the appropriate valorisation pathways.

Central to the deliverable is the harmonized wood classification framework, which defines clear material categories and quality criteria to support downstream valorisation processes. The modular design, featuring the dual-delta main sorting line, XRF with air nozzles, XRT line, and dedicated human-robot collaboration stations, allows for dynamic adaptation to varying input stream characteristics and evolving regulatory requirements. The deliverable provides the technical specifications as well as the functional requirements necessary to provide a roadmap for actualization and operation in the real-world physical space.

6.2. Future Work

One of the main objectives of W2W project is to develop and demonstrate new valorisation routes for wood and glass streams. On that premise a novel sorter design for wood and glass has been developed, based on the current-state-of-the-art in sensors, perception, machining and tooling, and as it follows from the thorough analysis performed on wood samples for determining an optimal and feasible on-the-fly resulted sorting and classification.

Our analysis and design process will materialize with the consequent phase 2 and the respective tasks T6.3-4 of WP6 with the installation thorough testing and the ultimate delivery.

7. REFERENCES

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