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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:**

**2.13 Characterization of value chains v1**

Work Package: 2

**LEAD BENEFICIARY:**

**RISE Research Institutes of Sweden (RISE)**

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# Publishable summary

Improved resource efficiency and circular economy are vital for a more sustainable use of resources. In Task 2.5 of Theseus, inclusive value chains will be characterized and analysed. Relevant key performance indicators (KPIs) that clearly describe the flow of resources and allow monitoring of the progress and impact of alterations to the value chain will be defined. The KPIs will also serve to capture demands and requirements of different stakeholders in the value chains.

As the value chains of Theseus are complex and, to some degree, intertwined with each other, forthcoming work in Task 2.5 will aim to elicit the competition of the same resources and how that should be addressed with consideration to stakeholder value, resource efficiency, circular economy etc. When all the Theseus technologies are applied in the different value chains the characterization of the value chains will be clearer due to a better understanding of the challenges at hand for each stakeholder. Gathering the feedback from stakeholders will be an important activity to achieve a zero-waste hub in the Attica region as well as in other parts of the EU.

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# Abbreviations

| Abbreviations | Full name |
|---|---|
| **HSI** | Hyperspectral Imaging |
| **KPI** | Key performance indicator |
| **GHG** | Greenhouse gases |
| **MSW** | Municipal Solid Waste |

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# 1 Introduction

Improved resource efficiency and moving towards a circular economy are key actions to avoid depletion of resources. An increased understanding of the value chains of different products and materials further enables the identification of measures that can be taken to decouple economic growth from resource use, through e.g., alternative uses of resource and waste flows/residual streams, changes in transaction points, and cascading of resources. In Task 2.5 of Theseus, value chains of studied resources will be described, characterized, and validated. The studied resources are mainly textiles, different types of plastics, and construction and demolition waste. The Attica region of Greece constitutes the context, where relevant stakeholders for each value chain are part of Theseus, but additional stakeholders in the region will be included in the analysis.

The purpose of Task 2.5 is to identify relevant KPIs that enable monitoring of the studied value chains in terms of how alterations of the resource flows impact the environment, social, and economic sustainability. Accurately defined KPIs allows for an improved understanding of not only the current sustainability of the value chains, but also what types of changes have the most positive impact on improved resource efficiency and accelerate the circular economy. Furthermore, by capturing the perspectives of the stakeholders involved regarding aspects such as risks, quality requirements of feedstocks, end-user requirements etc., the KPIs also serve to facilitate a better understanding of individual and common challenges among the stakeholders and can also promote future collaboration and industrial symbiosis potentials.

## 1.1 Purpose of the deliverable

This deliverable provides a first overview of the value chains in the Theseus project as well as identifying actions remaining in the task. In the task, the Theseus value chains will be qualitatively characterized, defined, and described in detailed to enable monitoring of different sustainability dimensions (such as environmental, social, and economic sustainability). This includes defining KPIs that captures progress and potential alterations to the studied value chains.

This deliverable, as well as forthcoming deliverables of Task 2.5 (D2.14 and D2.15), does not aim to address the value chains in quantitative terms. Other Tasks in WP2 put more emphasis on the quantification of resource flows, while Task 2.5 focuses on quality requirements, definition of KPIs, etc. With that said, quantitative values in the value chains will be included if available and relevant.

This deliverable presents the results so far and the method applied for how the results have been achieved. Furthermore, we also describe what outcome is expected going forward and what parts of the described methodology that is going to be employed to receive the expected results. The expected results will also be coordinated with other related tasks, in particular Task 2.3 and Task 2.4, that use them as input.

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# 2 Method

To meet the purpose of Task 2.5, it is necessary to include the different stakeholders' perspectives. The requirements on the so-called transaction points for the stakeholders need to be made clear. Transaction points in a value chain can be, for example, when a material or resource flow exchanges ownership, including being a point that can be subjected to changes such as being replaced with another feedstock. In general, the following types of stakeholders are usually involved in different parts of the value chain:

- Production,
- Manufacturing/processing,
- Distribution,
- Warehousing/wholesale,
- Sales,
- User phase,
- Disposal/waste.

Changes to the value chain involve first defining the current status of the studied value chain and defining what could potentially be a future value chain for the studied resources. This involves elucidating things such as the possible changes that can be made in the flows of the value chain, finding a new recipient for waste, and whether waste flows can and should be circulated back into the same or another value chain or if efforts rather should be made on reducing the waste flow.

To achieve this, the following overarching method is applied:

1) Discussion with partners in Theseus (task leaders of processing material technologies),
2) Initial characterization and description of the value chains based on proposal and material from the actors involved,
3) Initial list of relevant value chain KPIs,
4) Collaborative workshops for each of the value chains with actors involved,
5) Revision of characterization of value chain and the defined KPIs.

The first step involves online-discussion with partners in Theseus with a good insight on material flows in the Theseus value chain. These discussions have been based on defining, where possible, requirements, current status of application (i.e., TRL), demands (e.g., amounts/flows), for different transaction points in each value chain, in order to provide a better understanding of the characteristics of these value chains. Additional information has been gathered by email from stakeholders, but so far responses have yet to be received from all relevant stakeholders within Theseus.

The next steps (2 and 3) involve creating a first description (characterization) of the value chains, involved stakeholders, and KPIs. This is done internally by the RISE team, based on the information provided by stakeholders as well as relevant literature on KPIs for value chains. By doing this, a first version on the categorization of stakeholders, types of flow, amount, etc., is done. The purpose of the first version of value chain characterization is to initiate the discussion in the subsequent workshops, where the first versions are revised based on the further input from stakeholders.

Steps 1-3 have been carried out, meaning that the results presented in this deliverable is based on the data described. The upcoming steps are expected to be completed by the end of the project.

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For each defined value chain, step 4 involves holding a workshop with involved stakeholders. Afterwards, the characterization of the value chains, potential for change/alterations to the value chains, and defined KPIs will be revised accordingly to the outcome of the workshop considering the different perspectives of stakeholders on risks, quality, etc.

## 2.1 Collaborative workshop

As mentioned in the task description, a collaborative workshop is at the heart of the task of describing the value chains of interest. The reason for this is to be able to capture each involved stakeholders' perspective on the questions at hand, and what is important particularly in the transaction points of different flows. The setting of a workshop provides further potential of valuable input by using additional set of tools (workshop activities) and enabling dialog between stakeholders in comparison to interviews. The collaborative workshops are led by the RISE team.

While the main activities of the workshop have not yet been set, they will be designed to address the following:

*Refining the value chain of materials and resource flows.* The first version of the value chains, developed by task team members through discussions with partners within Theseus and based on literature, will be reviewed and revised accordingly to be useful in the perspectives of the stakeholders. The detailed level of categorization, description, and characterization of value chain flows needs to be proven relevant.

*Elicit different perspectives on values and risks*. Alterations to the value chain, whether it implies change of transaction points for flows or changes in amount (e.g., improved efficiency or increased flows).

*Balancing different values.* The values held by stakeholders in the value chain need to be clearly defined to move forward on aspects such as risk sharing, sharing of costs, etc.

*Identification of additional stakeholders.* The discussion between stakeholders can erase additional need for other stakeholders not part of Theseus that could hold an interest to the flows or be affected by changes to the value chain.

*Revision of initial list of KPIs.* The defined KPIs from the first list based on literature will be addressed and revised to select the indicators that are relevant for monitoring progress and changes to the transaction points in the value chains.

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# 3 Results

Based on the outcome of the implementation of the first steps of the described method, the material flows are divided into three different value chains: the textile value chain, the plastic value chain, and the construction and demolition waste value chain. Each value chain involves different technologies applied as well as materials. Furthermore, some materials might be used in more than one value chain.

The initial discussions with partners within Theseus show that the readiness level of the pilots of Theseus value chains differs among the involved stakeholders. Some actors are already fully operating in their processes, and part of their goal within Theseus regards upscaling the existing processes. At the same time, some emerging, promising technologies for increased circularity of streams are implemented in the studied value chains, however, in some cases, it is still at a lab-scale level. Relating this to the aim of Task 2.5 implies that some stakeholders might have different prerequisites in how they perceive the development of KPIs. Some actors might already have KPIs in place that they monitor, while others have yet to define KPIs.

## 3.1 Generic key performance indicators for value chains

Most common metrics (KPIs) that are monitored in industry for energy, material etc., are normally facility-level metrics (e.g., energy consumption, water consumption) or product-level metrics (e.g., SEC) (Meinrenken et al., 2014). Indicators measuring the performance of circular economy need data from the multiple sources and stakeholders that are involved in the value chain (Pidikiti et al., 2023). Saidani et al. (2019) provides a taxonomy of circular economy indicators following three different levels of indicators:

- Macro level - cities, regions, nations,
- Meso level - businesses, industrial symbiosis,
- Micro level - products, components, materials.

A distinction can be made between indicators that monitor the "transition progress" and their effects, (Potting et al., 2016). *Temporal scope* refers to ex ante, ex durante, and ex post evaluations. Furthermore, KPIs can be either action-oriented or information-oriented, generic or sector specific, and of quantitative or qualitative nature.

For firm-wide KPIs, an example of a list could be (Meinrenken et al., 2014):

- Life cycle CO2-eq.,
- Raw material amounts (tons),
- Raw material amounts (cost),
- Facility consumption of energy types (kWh),
- Facility consumption of energy types (cost),
- Water consumption (litre),
- Water consumption (cost),
- Transportation types (tonkm),
- Transportation types (cost),
- Disposal streams (tons).

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These KPIs use inputs such as raw material cost, amount of raw material, energy consumption, water consumption, emission factor of materials, transportation distances, refrigeration times, shelf times, and disposal characteristics.

A selection of indicators defined by de Pascale et al. (2021) for circular economy is shown in Table 1.

**Table 1: A selection of indicators for circular economy (de Pascale et al., 2015). Micro = circular economy operating at product, company, and customer level. Meso = medium level, e.g., eco-industrial parks. Macro = city, region, national, and larger level.**

| Indicator | Description | Indicator level |
|---|---|---|
| **Reuse potential indicator** | Reuse potential value = (net marginal revenue from sale of transformed materials - disposal cost) / quantity of a reused material | micro |
| **Circular economy index** | CEI = material market value of recycler / material value entering the plant | micro |
| **Material circularity indicator** | MFA | micro |
| **Eco-cost value ratio** | Costs for prevention of material and energy depletion / market value of products and services delivered | micro |
| **Circular economy indicator** | Semi-structured interviews with an overall score | micro |
| **Longevity indicator** | Consider the life of materials in products | micro |
| **Material reutilization score** | Recyclability potential of a product | micro |
| **Product level circularity metric** | Economic value of recirculated elements divided by economic value of all elements. | micro |
| **Value-based resource efficiency indicator** | MFA; Value added divided by value of inputs, except for labor | micro |
| **Circularity calculator** | % of product or part in following cycles: Remanufacturing, refurbishment, recycling. Shows the potential mass and value flows of a product, since the diverse elements can be recycled, remanufactured, or reused. | micro |
| **Quantitative Assessment of Economic and Environmental Aspects** | IS exchanges are defined as downward chains, quantity of rescued raw material is evaluated | Meso |

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| Indicator | Description | Indicator level |
|---|---|---|
| **Method for analysis of INDustrial energy systems (MIND)** | Mixed integer Linear Programming used to study energy and material flows | Meso |
| **Resource productivity** | MFA (systematic assessment of the flow and stock of materials within a system). For transportation sector. Direct material output and passenger turnover. | Meso |
| **Resource productivity indicator (RP)** | RP = industrial added value of the companies in the production chain / inputs to the IS system | Meso |
| **Eco-efficiency indicator** | EEI = economic performance indicator / environmental performance indicator | Meso |
| **Eco-Efficiency performance** | MFA | Meso |
| **Industrial Symbiosis Indicator (ISI)** | Determined as the rate between input and output momentum. | Meso |
| **Wastewater circonomics indicator** | *Will be described later on if adopted.* | Meso |
| **Material flow analysis and accounting (MFA) at macro level** | *Will be described later on if adopted.* | Macro |
| **Circularity Indicators based on the MFA approach** | *Will be described later on if adopted.* | Macro |
| **MFA of the Swiss waste management system** | Recycling Rate (RR) = Recovered material / Waste produced | Macro |

## 3.2 Textile value chain

From 1 January 2025 EU Member States are obligated to have separate collection of textiles according to the amendments of the Waste Framework Directive (2008/98/EC). The European Commission is also in the process of establishing rules on how to "…*make producers responsible for the full lifecycle of textile products*" (European Commission, 2023). That also includes how producers can support the overall management of textile waste.

The successfulness in the pursuit of increased textile streams in the higher levels of the waste hierarchy (reduce, re-use, and recycling) depends on key factors such as upscaling of technology with high effect on

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reduced environmental impact, increased demand on recycled textile material, and clear targets, monitoring regarding the upcoming producers' responsibilities, among other things.

The textile value chain of the Attica region as of today is shown in Figure 1.

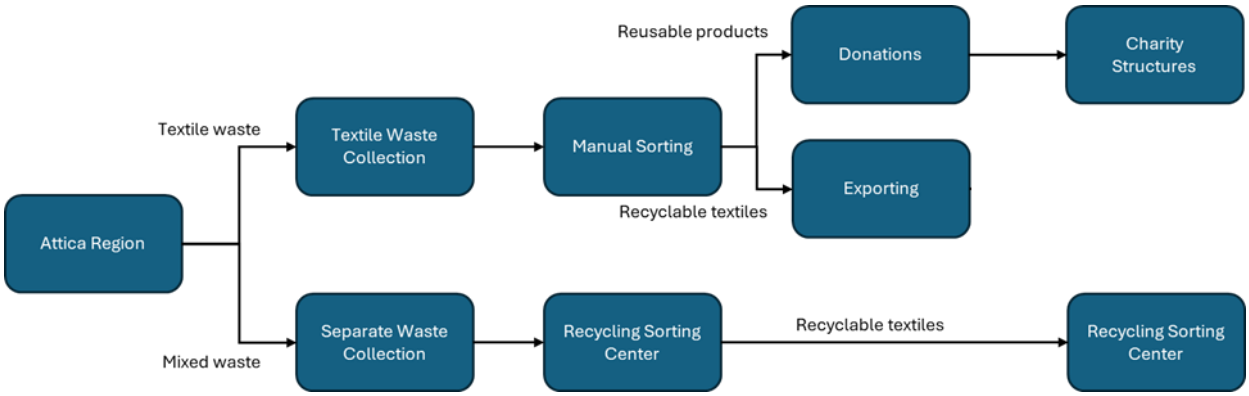



**Figure 1: Current textile value chain, Attica region.**

Clothes and textiles in the Attica region are collected in textile (purple coloured) bins, and handled by RECYCOM. Only in the municipality of Athens in total, there are about 250 bins[1]. In the purple bins, clothes, textiles, garments, and shoes are collected. These are sorted into reusable items (for charity etc.) and recyclable items, and those that cannot be used or recycled are sent to landfill/incineration.

At present, the sorting of textile is carried out manually. Those textiles and clothes that are deemed reusable are donated to charity while the other recyclable textiles are exported. With the implementation of an automated sorting system the capacity is expected to increased by approximately 30%.

In addition, municipal solid waste (MSW) from the Attica region will be used as another source of textiles, and especially from these collected in blue bins (packaging recyclables, a part of total MSW). In Greece, the average composition of MSW is:

- Paper 29%,
- Biowaste (organic) 39%,
- Plastic 12%,
- Glass 4%,
- Textiles 2%,
- Others 14%.

The fraction "others" includes waste such as diapers and other combustible and incombustible materials. Whether the composition of MSW is similar in the Attica region or not needs to be discerned during the continued work of Theseus as well as a more accurate composition of waste from the blue bins specifically.

[1] https://www.recycom.gr/%CE%B4%CE%AE%CE%BC%CE%BF%CF%82-%CE%B1%CE%B8%CE%B7%CE%BD%CE%B1%CE%AF%CF%89%CE%BD/

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WATT sorting facility plant Fyli in Attica has a capacity of 50,000 tons/annually. WATT sorting facility in Koropi, Attica (Theseus predicted activities) has a capacity of 20 tons/hour[2], i.e., max 175,000 tons/annually.

The separate waste collection (blue bins) handled by WATT for these 2 facilities is up to 225,000 tons/year. With the assumption that 2% of the MSW is textile, it means that up to 4,500 tons of textiles per year can be potentially sorted from the MSW. It also means that the other fractions have a waste stream of about 220,500 ton per year. This is not including any other facilities that could provide additional capacity.

Textiles collected from the purple bins, will be automatically sorted (with RGB and HIS technology) into three categories: Natural, thermoplastics, and mixed fibre. Textile separation from MSW will be improved by using AI-driven machine vision. Shoes from purple bins cannot be recycled to e.g., new material, since they are too "complex", they can only be reused, repaired, or used for energy recovery.

The expected new textile value chain within the Theseus project is shown in Figure 2. As it is work in progress the final value chain might be different.

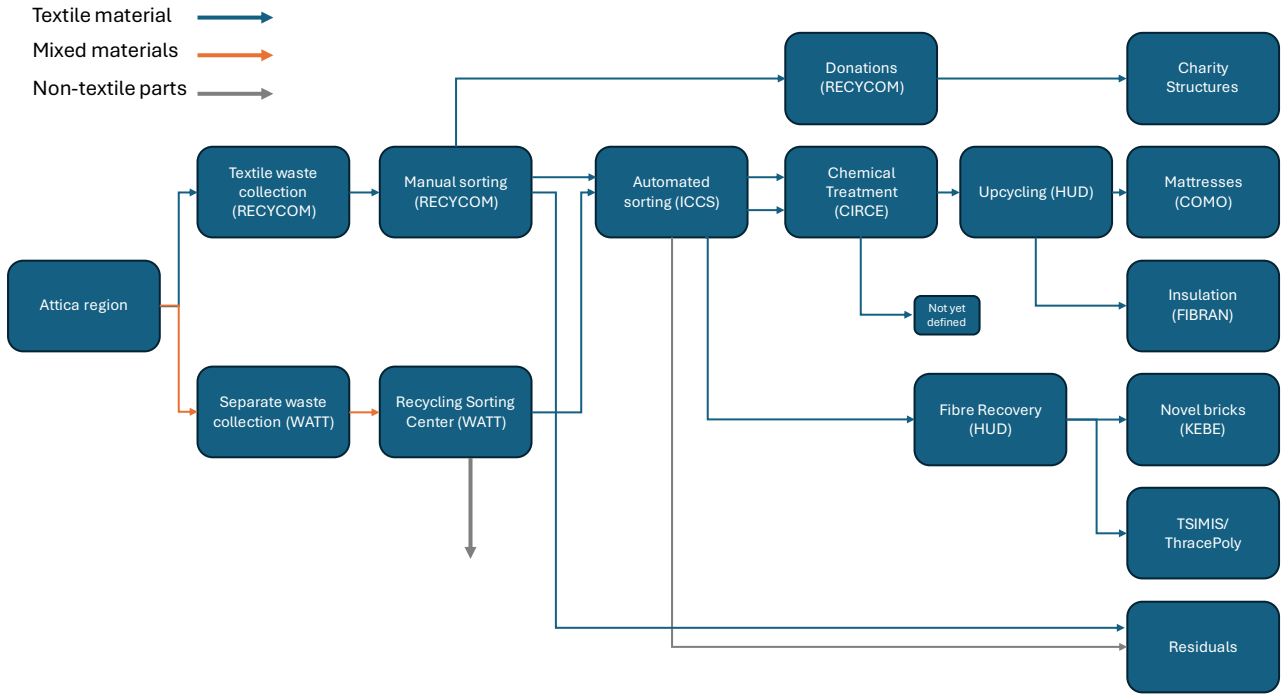



**Figure 2: New (expected) textile value chain in the Theseus project.**

Glycolysis will be performed on the textile fibres by CIRCE. This is already explored in a sister project named *Redol.* HUD will conduct chemical treatment on the textile fibres. There will be a spinning process to obtain better properties of the fibres. A block of fibres will be used to introduce directly into Fibrans products, in

[2] https://sepan.gr/en/members/watt/

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particular insulation materials. CIRCE will carry out a purification step, since a 100% pure monomer is required.

The textile value chain will result in different end products and with this there are several different end users of the process. Aspects that are to be included in the workshop with stakeholders are: Capacities or quantitative and qualitative description of flows.

### 3.2.1 Recycled textiles in products in Theseus value chains

Fibran, manufacturer of insulation products, will need a large volume to be able to test the fibres in their product: A minimum of 200 kg for testing. They will probably mix it with other fibres as it is not certain that they can use 100% recycled material. If the fibres should be recycled more times, it is estimated that they can only be cycled a maximum of five times if it is a thermochemical recycling treatment process. After five times, the properties of the fibres are not useable in Fibran's end-products anymore. Furthermore, There are many quality features that need to be met in order to be able to replace the stone wool with recycled textile fibers. Examples of quality requirements are specific flash points, purity of fibres, length of fibers and conformity of the fiber at elevated temperatures.

Further details on the requirements of Fibran, as well as the requirements for the other stakeholders (manufacturers of end-products), namely novel bricks, mattresses, and plastic products, will be defined in the upcoming working months of the project.

### 3.2.2 Textile value chain: key performance indicators (KPIs)

The process KPIs identified from the literature for the textile value chain (Table 2) have been grouped in three categories connected to: 1. the whole value chain, system perspective; 2. local/regional perspective, and 3. to each of the individual processes that are part of the value chain.

NOTE: The KPIs listed below are a preliminary compilation. Meetings with the different stakeholders are needed for a better understanding of their process that will lead to more concreate KPIs. The collaborative workshops will further revise the suggested KPIs.

Table 2 presents the most relevant KPIs identify to the textile value chain illustrated in Figure 2, viewed from a system perspective. The reflect efficiency, effectivenesss, and sustainability for the entires system, from collection to final disposal or reuse.

**Table 2: KPIs for the textile value chain.**

| SYSTEM PERSPECTIVE<br>KPI | DESCRIPTION | UNIT |
|---|---|---|
| **Material recovery rate** | Ton of a specific product obtained after processing the textile waste collected per ton of textile waste | % |
| **Material recovery efficiency** | It evaluates the efficiency of recycling processes in recovering materials for reuse. It not only measures | % |

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| SYSTEM PERSPECTIVE<br>KPI | DESCRIPTION | UNIT |
|---|---|---|
| | the volume of materials recycled but also the quality of the recycled output, which is crucial for ensuring that recycled materials find their way back into the production cycle. (ESG Voices, 2024) | |
| **Processing cost per ton** | Measures total cost per ton of material processed. | €/ton |
| **Chemical[3] recovery rate** | Mesure of the efficiency of recovering and reusing chemicals used in different parts of the value chain. This KPI can be used as a indicator of environmental impact of the processes. | % |
| **Energy recovery rate** | Percentage of energy that is recovered from the system compared to the total energy input or potential energy available | % |
| **Energy consumption per ton** | Measures total energy consumption (electricity, gas, water) per ton of material processed. | kWh/ton |
| **Water recovery rate** | Mesures how efficient water is used in processes is recovered and resused, rather than beind discharged or wasted. | % |
| **Emission generated/avoidedper ton of textile waste processed** | Measure of the value chain's environmental GHGs emissions, crucial for driving sustainable practivies and regulatory compliance. | Ton CO2/ton |
| **Revenue per ton of material recycled** | (Average) revenue generated per ton of recycled material. This KPI is crucial for production and pricing planning. | €/ton |
| **Reuse potential indicator** | Net marginal revenue from sale of transformed materials - disposal cost) / quantity of a reused material | |
| **Circular economy index (CEI)** | Material market value of recycler / material value entering the plant | % |

[3] It refers to any type of chemicals used in the process: solvents, reagents or catalysts.

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The relevant KPIs from a local and/or regional prespective identified for the textile value chain (Figure 2) are presented below in Table 3. These KPIs will reflect the context of the specific geographic area. This approach helps to tailor strategies to local/regional conditions, regulations, resource availability, and environmental impact, as well as measure more accurately their performance.

Table 3: Local/regional perspective KPIs

| LOCAL/REGIONAL PERPESCTIVE | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Textile waste reduction score** | It measures the success of programs designed to reduce the total amount of textile waste generated | % |
| **Public Participation rate** | Level of community engaged in textile waste sorting (purple bins) | %, Kg/capita |
| **Textile waste generated per person** | Amount of textile waste generated per person per year | Kg/capita,y |
| **Total residual waste generated per person** | Amount of residual waste generated per person per year | Kg/capita,y |
| **Total waste generated per person** | Includes all the waste fractions that can be source sorted + residual waste per person per year | Kg/capita,y |
| **Total waste source sorted per person** | Amount of source sorted waste generated per person per year | %, Kg/capita |
| **Textile waste recovery/collection rate for Attica** | Be careful because this one includes wrong sorted and contaminated items | % |
| **Textile waste recycling rate for Attica** | Percentage of textile waste that is successfully recycled within the Attica region, compared to the total among of textile generated in the same area. | % |
| **Total revenue for handling textile waste** | (Average) revenue generated from activities related to the collection, processing, recycling and selling of the textile per ton of textile waste. | €/ton |

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| | | |
|---|---|---|
| **Total cost for processing textile waste** | Measures the total cost of handling and treating textile waste along the value chain | €/ton |
| **Access to textile waste collection in Attica** | Percentage of population with convenient access to textile waste collection systems | % |

The identified KPIs related to the collection of textile waste in specific bins in the Attica region by RECYCOM (see Figure 2) are presented in the the following table (Table 4).

Table 4: Textile waste collection KPIs

| TEXTILE WASTE COLLECTION<br>KPI | DESCRIPTION | UNIT |
|---|---|---|
| **Sorted textile waste collection coverage ratio** | The percentage of the target area covered by the collection system (where the bins are located) | % |
| **Textile waste sorted per person** | | Kg/capita,y |
| **Waste diverted from the mixed residual fraction rate (Diversion rate)** | The percentage of the total waste that is diverted from the residual waste by being source sorted.<br>How to calculate: (Total textile collected/total waste collected) x100 | % |
| **Public Participation Rate** | | % |
| **Collection frequency rate** | It is about how efficient the service is according to the scheduled frequency<br>How to calculate: (number of on-time waste collections/total scheduled collections) x 100 | % |
| **Bins average fill level** | It gives an indication to which degree the bins are full when they are emptied and/or whether the number of bins is enough How to calculate it: (total volume of waste in the bins when emptied / total volume of the bins) x 100 | % |
| **Customer satisfaction score** | Level of satisfaction customers have with the collection system. Examples: are there sufficient bins available? Efficiency of the system? Distance to their home? Are those places safe? If they are happy, they will continue using the service.<br>How to calculate: (Number of satisfied customers/total number of customers) x100 | % |

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| TEXTILE WASTE COLLECTION | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Tons of $CO_2$ emitted per ton of textile waste collected** | Includes the one that is wrong sorted. It refers to transportation/logistics. | Ton $CO_2$/ton |
| **Processing cost per ton** | Measures total cost per ton of material processed. | €/ton |
| **Sorted textile waste collection coverage ratio** | The percentage of the target area covered by the collection system (where the bins are located) | % |

The relevant KPIs identified for manual sorting of textile waste by RECYCOM (more details of the textile value chain in Figure 2) are listed in Table 5.

Table 5: Textile manual sorting KPIs

| MANUAL SORTING | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Material recovery rate** | Percentage of total textile waste that was sorted correctly and is sent to automated sorting | % |
| **Contamination rate (in textile collected)** | Percentage of the total material collected that was wrong source sorted. (i.e. plastic packaging, contaminated textiles…). Wrong source sorted items increase the need for bins, cost for transportation and sorting.<br>How to calculate: (Weight of wrong sorted items / total weight of sorted collected material) | % |
| **Textiles to donations rate** | Rate of the collected textiles that can be sent to donation. | % |
| **Energy consumption per ton of textile sorted** | Measures total energy consumption per ton of textile sorted. As an example, in conveyor belts are used in many facilities with manual waste sorting. | kWh/ton |
| **Manual sorting costs per ton of waste textile** | Measures the total cost of manually sorting textile waste collected per ton of textile waste going through this process. | €/ton |

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Table 6 presents the main KPIs identified in relation to the collection of residual mixed waste containing textile waste carried out by WATT, which represents a stage in the textile value chain under analysis in this chapter (Figure 2).

Table 6: Textile separate waste collection KPIs

| SEPARATE WASTE COLLECTION | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Percentage of textile in the residual waste** | Porcentage of textile that is found in the residual waste generated by the households. | % |
| **Collection frequency rate** | It is about how efficient the service is according to the scheduled frequency<br>How to calculate: (number of on-time waste collections/total scheduled collections) x 100 | % |
| **Bins average fill level** | It gives an indication to which degree the bins are full when they are emptied and/or whether the number of bins is enough How to calculate it: (total volume of waste in the bins when emptied / total volume of the bins) x 100 | % |
| **Customer satisfaction score** | Level of satisfaction customers have with the collection system. Examples: are there sufficient bins available? Efficiency of the system? Distance to their home? Are those places safe? If they are happy, they will continue using the service.<br>How to calculate: (Number of satisfied customers/total number of customers) x100 | % |
| **Tons of CO2 emitted per ton of textile waste in the residual waste or per ton of residual waste collected** | It refers to transportation/logistics. | Ton $CO_2$/ton |
| **Cost per ton of mixed waste collected** | Includes the one that is wrong sorted. It refers to transportation/logistics | €/ton |

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The main KPIs identied in relation to the the sorting of textile waste from the residual mixed waste at the WATT facility are presented in Table 7.

Table 7: Textile recycling at sorting center KPIs

| RECYCLING SORTING CENTER<br>KPI | DESCRIPTION | UNIT |
|---|---|---|
| **Material recovery efficiency rate** | Percentage of total textile waste in the mixed waste that was recovered (automated sorting). It not only measures the volume of materials recycled but also the quality of the recycled output, which is crucial for ensuring that recycled materials find their way back into the production cycle. (ESG Voices, 2024) | % |
| **Energy consumption per ton textile sorted /mixed waste** | Measures total energy consumption per ton of textile sorted or mixed waste form the residual mixed waste | kWh/ton |
| **Cost per ton of textile waste mechanically sorted** | Measures the cost of sorting textile waste from the residual mixed waste per ton of textile waste | €/ton |
| **Processing cost per ton of residual waste** | Measures the cost of sorting textile waste from the residual mixed waste per ton of residual mixed waste | €/ton |
| **Tons of CO2 emitted per ton of textile waste sorted from the mixed waste** | Includes logistics | Ton CO2/ton |
| **Equipment utilization rate** | Measures the percentage of time equipment is in active use, reflecting operational efficiency and capacity utilization. (Finmodelslab, 2025) | % |

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The main KPIs identied in the automated sorting of textile waste at the ICCS facility are presented in Table 8. In this part of the process the textile waste is sorted out different categories with the use of AI-driven sorting technology.

Table 8: Automated sorting KPIs, ICCS

| AUTOMATED SORTING, ICCS | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Material recovery efficiency rate** | Percentage of total textile waste that enters the automated sorting plant that actually goes to chemical recycling | % |
| **Energy consumption per ton textile automated sorted** | Measures total energy consumption per ton of textile sorted | kWh/ton |
| **Cost per ton of automatically sorted textile waste** | Measures the cost of sorting textile waste from the residual mixed waste per ton of textile waste | €/ton |
| **Tons of CO2 emitted per ton of textile waste sorted automatically** | Includes logistics | Ton CO2/ton |
| **Equipment utilization rate** | Measures the percentage of time equipment is in active use, reflecting operational efficiency and capacity utilization.(Finmodelslab, 2025) | % |

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Textile that are collected speratly and identified as resusable during the manual sorting are donated to charity organizations. RECYCOM is responsible for managing this process (Figure 2) and the identified KPIs for this process are listed in the table below (Table 9).

Table 9: Donations KPIs (Recycom)/Charity

| DONATIONS (RECYCOM)/ CHARITY | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Material donated to charity rate** | Percentage of total textile waste that is collected separately that actually goes to charity | % |
| **Processing costs per ton of textile donated** | Measures the cost of handling the resuable textiles sorted manudally sorted per ton of textile donated | €/ton |
| **Tons of CO2 emitted per ton of textile distributed to charity** | Includes logistics | ton CO2/ton |
| **Energy consumption per ton of textiles sent to charity** | Measures total energy consumption per ton of textile donated to charity | kWh/ton |

In the automated sorting, textiles are sorted into three categories: natural, thermoplastics, and mixed fibre. (Figure 2), The identified KPIs for this process are listed in the table below (Table 10).

Table 10: Chemical treatment KPIs (Circe)

| CHEMICAL TREATMENT (CIRCE) | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Chemical usage efficiency** | Amount of chemical used per unit of fabric processed | Kg/kg |
| **Right Frist Time (RFT) rate** | Percentage of batches that meet quality standards without reprocessing | % |
| **Water consumed per ton of textile processed** | Water used per ton of textile processed | l/ton |
| **Wastewater generated per ton of textile** | Wastewater generated per ton of textile processed | l/ton |
| **Solvents consumed per ton of textile p** | Solvents used per ton of textile processed | l/ton |

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| CHEMICAL TREATMENT (CIRCE) | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| **Energy consumption per batch/ton of textile processed** | Measures total energy consumption per batch or ton of textile processed | kWh/barch or kWh/ton |
| **Downtime due to chemical issues** | Time lost due to chemical-related problems | h |
| **Cost per ton of textile treated (per unit treated)** | (Averge) costs associated to the chemical treatment of textiles per ton of textiles treated | €/ton |
| **Total revenue per ton of chemically processed textile** | (Average) revenue generated from the chemically treating the textiles | €/ton |
| **Tons of CO2 emitted per ton of textile waste processed** | Includes logistics | Ton CO2/ton |

The main KPIs identified for the fiber recovery process that HUD is responsible for are listed in the table below (Table 11).

Table 11: Fiber recovery KPIs (HUD)

| FIBER RECOVERY (HUD) | | |
|---|---|---|
| **KPI** | **DESCRIPTION** | **UNIT** |
| ***This will be developed later on in Task 2.5 and included in subsequent deliverables.*** | *This will be developed later on in Task 2.5 and included in subsequent deliverables.* | |
| | | |
| | | |

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The KPIs of the upcycling process that HUD is responsible from are listed in Table 12.

Table 12: Upcycling KPIs (HUD)

| UPCYCLING (HUD)<br>KPI | DESCRIPTION | UNIT |
|---|---|---|
| **Chemical usage efficiency** | Amount of chemicals used per unit of fabric processed | Kg/kg |
| **Right Frist Time (RFT) rate** | Percentage of batches that meet quality standards without reprocessing | % |
| **Water consumed per ton of textile** | Water used per ton of textile processed | l/ton |
| **Wastewater generated per ton of textile** | Wastewater generated per ton of textile processed | l/ton |
| **Energy consumption per batch/ton of textile processed** | Measures total energy consumption per batch or ton of textile processed | kWh/barch or kWh/ton |
| **Cost per ton of textile treated (per unit treated)** | (Averge) costs associated to the chemical treatment of textiles per ton of textiles treated | €/ton |
| **Total revenue per ton of material upcycled** | (Average) revenue generated from the chemically treating the textiles | €/ton |
| **Tons of CO2 emitted per ton of textile waste processed** | Includes logistics | Ton CO2/ton |

Further KPIs for the end stages in the textile value chain will be developed and characterized later in the project, as well as characterizing residual flows from different steps in the value chains.

### *3.2.3 Quality requirement of input material for textile*

This will be developed later on in Task 2.5 and included in subsequent deliverables.

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## 3.3 Packaging (plastic) value chain

The plastic packaging value chain is illustrated in Figure 3. The municipal solid waste collected in the blue bins is sorted at the separation and sorting station. Mixed urban waste will be sorted using optical monitoring technology, with plastic materials separated and directed to a designated container for recycling.

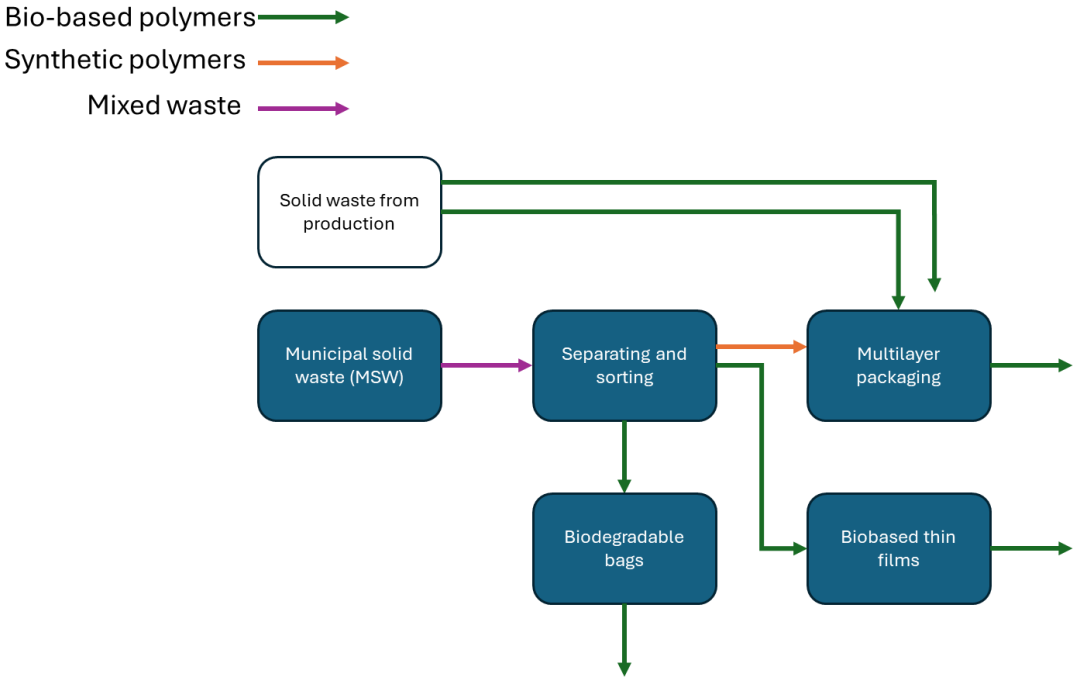



**Figure 3: Packaging (plastic) value chain.**

### *3.3.1 Bio-based films (Packaging upcycling)*

The separated (biodegradable) plastic waste will be mechanically shredded into a powder-like material by HMU , which will be used to produce recycled materials. The polymer powders could be either neat polymers or polymer blends with/without low-cost additives such as CaCO3, ZnO, SiO2 nanoparticles. Bio-based polymers such as PLA, PHA, PBS, PBAF or synthetic biodegradable polymers, Polycaprolactone (PCL), as well as PBAT, are relevant.

### *3.3.2 Biobased films for packaging*

Bio-based thin films for packaging will be developed using extracted bioplastics. Food waste that is rich in cellulose and polysaccharides, e.g., fruit peels, will be extracted and converted into a usable form of material. The extracted polysaccharides will be blended with other biopolymers (chitosan, gelatin) and additives (solvents, plasticizers, crosslinking agent) in various ratios to achieve desired mechanical and barrier properties.

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### 3.3.1 Electrospinning thin films

Pellets and fibers from recycled polymers with different functionalities for a wide range of applications using the electrospinning process and an extruder line. Through these process lines, various compounds will be incorporated into the polymeric structures to adapt or enhance specific properties, such as antimicrobial or barrier properties, and, thus, to extend the shelf life of the thin polymeric films. The incorporation of the compounds will be performed in three different ways: 1) direct encapsulation of compounds in the polymeric matrix through extrusion to produce batches of enhanced polymeric pellets. 2) encapsulation of compounds in the polymeric matrix by electrospinning to produce a micro/nano-composite powder, which will be co-extruded with conventional polymeric pellets, producing batches of enhanced polymeric pellets. 3) Encapsulation of compounds in the polymeric matrix through electrospinning for the development of a nanofiber film that will be coated onto conventional polymeric films. Thus, functional multilayer films will be fabricated. The developed products can have potential applications in packaging (garbage bags, medical packaging, food packaging), agricultural films and textiles sectors.

### 3.3.2 Plastics value chain: key performance indicators

NOTE: This section will be completed in later deliverables of Task 2.5 when the authors have received feedback on the work done for the KPIs of the textile value chain.

### 3.3.3 Quality requirements of input material (packaging)

NOTE: This section will be completed in later deliverables of Task 2.5 when the authors have received feedback on the work done for the KPIs of the textile value chain.

## 3.4 Construction and demolition waste value chain

The construction and demolition waste (CDW) value chain includes three main flows of materials: Glass, marble, and metals. Theseus will use CDW in brick production, utilizing the whole fraction, combinations and waste glass as binder in concrete products. The goal is to replace local materials where the feedstock will contain a minimum of 10% CDW and 6-8% ceramics waste. The performance of selected mortar mixtures, tailored for pre-cast elements and 3D-printability, will be validated in lab. Also, concrete recipes including glass will be tested at the ready-mixed concrete producer.

The initial version of the value chain of the construction and demolition waste of Theseus is shown in Figure 4.

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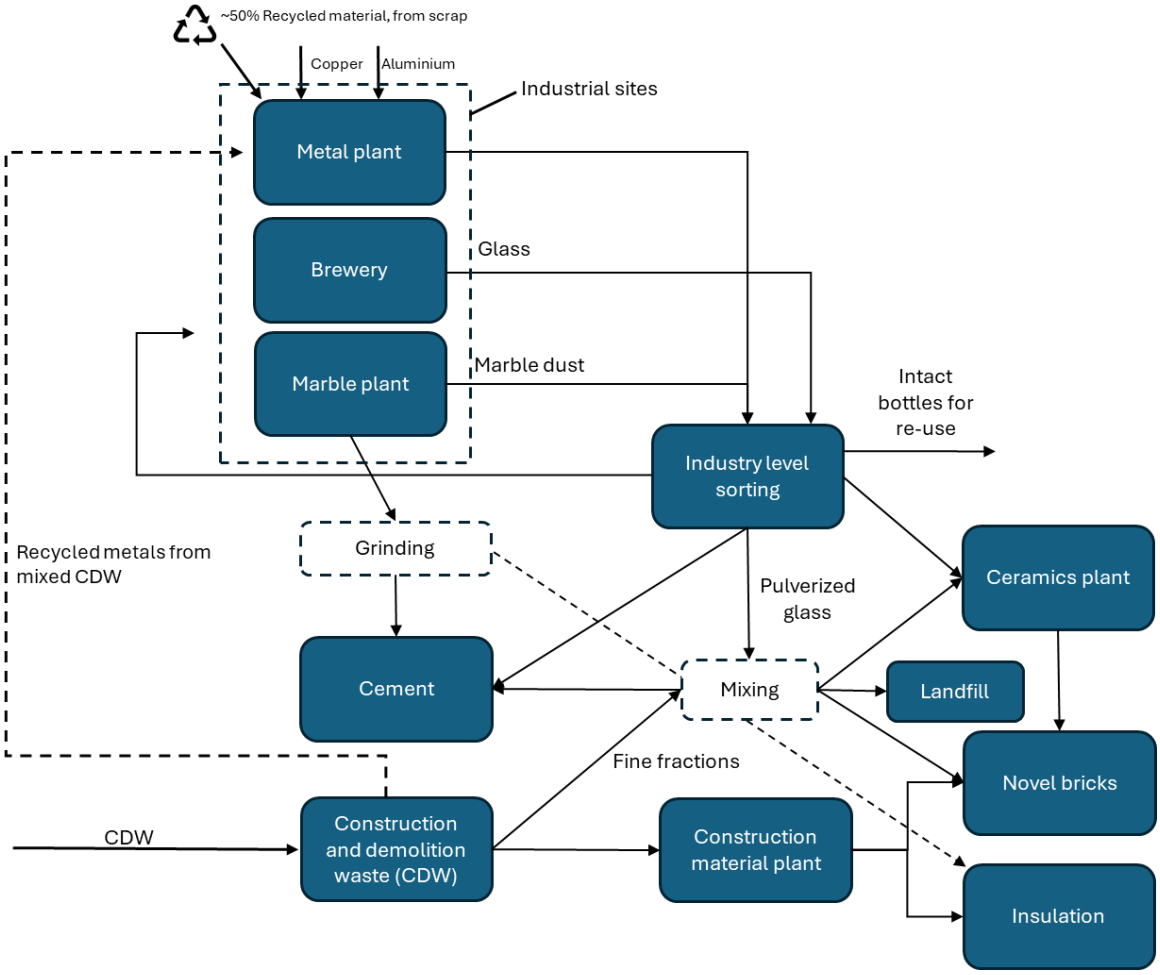



**Figure 4: Theseus construction and demolition waste value chain.**

### *3.4.1 Glass*

Glass-bottle sorting line: Intact bottles will be separated and grouped. Damaged ones will continue until the end of the line and end up in a container for recycling. CDW and waste glass will be refined with mechanical and wet separation technologies to develop different combinations of alternative raw materials and binders for brick production and concrete production.

Fine fractions of CDW and pulverised waste glass will be systematically designed for brick and concrete production. Techniques for designing used in the project are: mineralogy (XRD, TGA), microstructure (SEM/EPMA) and pozzolanic reactivity by determining the chemical bound water. Binder combinations will be optimised based on ceramic content, waste glass content, mineralogy and chemical leaching for both application routes.

Research has shown that when incorporating fine particles of glass in cement-based materials due to the favourable pozzolanic reaction which benefits the mechanical properties (Harrison et al. 2020).

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### 3.4.2 Marble

Marble dust is a common residual stream from the large marble mining industry in Greece. It has no secondary application today but is a promising additive in many different sectors. This will be analysed in different Theseus material streams.

The marble dust provided by Thrace Marble will be sent to the Technical University of Dresden (TUD) for pretreatment and testing in new applications. The pretreatment consists of grinding the marble dust into a fine particle powder. The marble powder has many possible applications, it can for instance be used in cement as a binding material and replace the current use of limestone. Since the mining of limestone is associated with large $CO_2$ emission processes there is a strong urge to find more sustainable replacements. Alternative usage of the marble powder is in insulation panels and bricks, but also as an additive in paint to change the rheology and make the paint more stable.

The marble powder can also be used in more innovative application such as foam concreate which is the final goal of the project. In order to be applicable in foam concreate the 3D printing capabilities need to be assessed and validated.

The availability of the marble dust is high in Greece since there are many marble mining activities in the region. The tests run by TUD in lab scale will start in the scale of approximately 3 kg. The amount could potentially reach up to 100-200kg for the later project trials.

Potential end users of the marble powder are typically concrete companies, but also chemical companies that produces paints of different kinds.

### 3.4.3 Metals

In Theseus, metals from mixed CDW will be extracted in the W2W sorter. In addition, an XRT cell for metal sorting will be implemented, customized and designed by TWI. Other processes to be implemented for the metal sorting line include shredding, balling, a vibrating conveyor belt, and multi sensor classification system of grading specific metals.

The receiver of the sorted metals will be HALCOR, in which the extended sorting line will be part of their facilities. HALCOR, being a producer of primarily copper and copper alloy products (e.g., copper alloys, copper tubes, brass alloys, brass tubes), using different raw materials including copper and aluminium. 2019, HALCOR had 4000 suppliers of which about two thirds were from Greece (HALCOR, 2020). Furthermore, the amount of copper emanated from scrap (mainly end-of-life products or companies processing metals) to their total metal purchases was about 50% (HALCOR, 2023).

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### 3.4.4 Construction and demolition waste value chain: key performance indicators

NOTE: This section will be completed in later deliverables of Task 2.5 when the authors have gotten feedback on the work done for the KPIs.

### 3.4.5 Quality requirements of input material CDW

NOTE: This section will be completed in later deliverables of Task 2.5.

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# 4 Concluding discussion

## 4.1 Conclusions

The Theseus value chains are complex and require further analysis and clarifications. Some of the value chains are partly merging or competing for the same resources, which needs to be assessed and evaluated. The work has recently started in WP5 where the preparatory and small-scale evaluation of the technologies of the different value chains are conducted. Once this work is up and running, the characterization of the value chains will become clearer. The work in this task can be a two-way street, it doesn't only have to be a characterization of the value chains but can also provide valuable feedback to the different stakeholders where the KPIs can provide guidance in achieving a zero waste hub.

## 4.2 Next steps and upcoming deliverables

The next step, as described in the Method, is to arrange collaborative workshops where the value chains are characterized in more detail. Depending on the timing in WP5 development, but the goal is to arrange these workshops in the autumn of 2025 and from this the next deliverable will be adapted and fine-tuned. Next steps also include collaboration across related tasks, such as Task 2.3 and Task 2.4. The KPIs will also be discussed with partners and adapted according to feedback and then the KPIs will be developed in the same framework for the other value chains.

Besides the further steps explained in the Method, actions to make sure the outcome of this Task is relevant for other tasks that make use of this will be taken. In Task 2.3, a material flow analysis (MFA) will be carried out where flows of resources will be described, including the amount. The outcome from Task 2.5 is going to be applied in Task 2.3, therefore, continuous communication of the progress of each task is of importance so the input to the MFA is useful and relevant.

In addition, as Task 2.4 aims to develop a roadmap for a larger scope (i.e., beyond Attica region), and how to integrate the activities of the Theseus project into EU, the results of Task 2.5 are relevant to facilitate the monitoring of sustainability regarding environmental, social, and economic impact of the activities. Communication together with Task 2.4 is therefore necessary to provide good information on these mentioned dimensions so that the indicators are of use in the development of action plans in Task 2.4.

Further steps will also consider, for example, KPIs that have been developed for value chains in previous EU project, the European Commission's requirements, other framework such as European Circular Economy Monitoring framework, Comprehensive Indicator Framework developed by NetZeroCIties and the CCRI Self-assessment tool. Information needed to assess sustainability of value chains will also be considered and the type of KPIs needed for the final users in the defined value chains.

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