Ref. Ares(2025)6958127 - 28/08/2025

THESEUS

Hub4Circularity

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

Grant Agreement No 101178059

DELIVERABLE 2.7

Material Flow Analysis v1

Work Package: 2 Development of the Theseus framework

LEAD BENEFICIARY:

Institute of Communication and Computer Systems (ICCS)

Delivery Date: 31.08.2025

Document Sheet

Project acronym	**Theseus**
Project full title	A First of a kind Hub for circularity demonstrator for Attica and peripheral regions
Programme	Horizon Europe
Topic	HORIZON-CL4-2024-TWIN-TRANSITION-01-38
Type of Action	HORIZON Innovation Actions
Grant Agreement	101178059
Start day	1 December 2024
Duration	60 months

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Document Information

Deliverable number	D2.7
Deliverable name	Material flow analysis v1
Lead beneficiary	ICCS
WP	2
Related task(s)	2.3
Type	R-Document, report
Reviewers	Elina Manoli (TUC), Babis Manousiadis (ICCS)
Delivery date	31.08.2025
Main author(s)	Stella Georgali (ICCS), Lucyna Lekawska-Andrinopoulou (ICCS), Alexandros Chachalis (TUC)
Contributor(s)	Eleftheria Dimopoulou (ICCS)

Dissemination level

PU	**Public**	X
SEN	Sensitive, limited under the conditions of the Grant Agreement	
Classified R-UE/EU-R	EU RESTRICTED under the Commission Decision No2015/444	
Classified C-UE/EU-C	EU CONFIDENTIAL under the Commission Decision No2015/444	
Classified S-UE/EU-S	EU SECRET under the Commission Decision No2015/444	

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Document history

Version	Date	Changes	Reviewer/Contributor
V0.1	01.08.2025	First version	Stella Georgali (ICCS), Lucyna Lekawska-Andrinopoulou (ICCS)
V0.2	04.08.2025	Addition of sections relating to the PSM tool & MFA results for textiles value chain	Alexandros Chachalis (TUC)
V0.3	06.08.2025	Review	Elina Manoli (TUC)
V0.4	27.08.2025	Reviewed version	Stella Georgali (ICCS), Lucyna Lekawska-Andrinopoulou (ICCS)
V1.0	28.08.2025	Final version	Babis Manousiadis (ICCS)

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Publishable summary

Deliverable D2.7 Material Flow Analysis v1 presents the initial methodological framework and baseline results of Task 2.3 in the THESEUS project, which establishes the first Hub for Circularity in Attica, Greece. The work applies complementary modelling approaches: the Process Simulation and Modelling (PSM) tool, providing “As-Is” and “To-Be” representations of waste value chains, and the Dynamic Probabilistic MFA (DPMFA) method, enabling time-dependent projections and uncertainty analysis.

Three priority waste streams are addressed: textiles, construction and demolition waste (CDW), and recyclable municipal solid waste (MSW). Early results confirm that in all three sectors landfilling remains dominant, separate collection is limited, and high-value recycling options are underdeveloped. Nevertheless, the analyses also highlight significant opportunities: expanding textile recovery through automated sorting, increasing CDW recycling rates by capturing metals, wood, and glass, and improving MSW performance through better packaging recovery and reduced contamination.

This deliverable establishes the foundation for more detailed, data-driven scenarios in subsequent versions (D2.8, D2.9), supporting the THESEUS ambition to make Attica a replicable model for industrial-urban symbiosis and circular innovation across Europe.

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Contents

1 Introduction 10
1.1 Purpose of the deliverable 10
1.2 Intended audience 10
1.3 Structure of the deliverable and THESEUS context 11
2 Material flow analysis for Sustainable Waste Management in Attica 12
3 MFA methodology and THESEUS approach 13
3.1 System definition and boundaries 13
3.2 Data collection approach 14
3.3 THESEUS MFA model 15
3.3.1 The Process Simulation and Modelling (PSM) Tool 15
3.3.2 Dynamic probabilistic material flow modelling 16
3.4 Assumptions, limitations, data gaps 16
4 THESEUS MFA use cases 17
4.1 Textiles sector 17
4.1.1 Textiles value chain in Attica – current practices and figures 17
4.1.2 Use case description 18
4.1.3 Preliminary results 18
4.2 Construction and demolition waste 25
4.2.1 CDW in Attica – current practices and figures 25
4.2.2 Use case description 25
4.2.3 Expected preliminary results 25
4.3 Recyclable Municipal Solid Waste 25
4.3.1 Recyclable municipal solid waste in Attica – current practices and figures 25
4.3.2 Use case description 26
4.3.3 Expected preliminary results 26
5 Discussion 26
5.1 Preliminary recommendations 26
5.2 Challenges encountered and strategies to address them 26
5.3 Next steps and strategic vision 27

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6 Conclusions 27
7 References 27
Annexes 29

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List of Figures

Figure 1 Links with other tasks 11
Figure 1: The 'As-Is' MFA model, as developed in the PSM tool 19
Figure 2: Results of the “As-Is” model MFA (quantities in tn/year)..... 19
Figure 3: The 'To-Be' MFA model, as developed in the PSM tool..... 21
Figure 4: Sankey diagram of the 'To-Be' MFA (quantities in tn/year)..... 22
Figure 5: Comparison of key material outputs for the 'As-Is' and 'To-Be' scenarios 23

List of Tables

No table of figures entries found.

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Abbreviations

Abbreviations	Full name
MFA	Material Flow Analysis
PSM	Process Simulation and Modelling
EPR	Extended Producer Responsibility
MFN	Material Flow Networks
AI	Artificial Intelligence
CE	Circular Economy
DoA	Description of Action
EC	European Commission
eSC	Extended Steering Committee
EU	European Union
GA	Grant Agreement
H4C	Hub 4 Circularity
IS	Industrial Symbiosis
I-US	Industrial Urban Symbiosis
PM	Project Management
PO	Project Officer
SC	Steering Committee
WP	Work Package
HMA	Electronic Waste Register

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1 Introduction

THESEUS is a Horizon Europe funded project, which develops a first-of-a-kind Hub for Circularity (H4C) in Greece, deploying systemic Industrial-Urban Symbiosis (I-US) concepts. The H4C activities are concentrated around the Attica region, which hosts the capital of Greece - Athens metropolitan area. The Athens Urban Area with almost 4 million inhabitants stands out due to its political, economic, maritime and cultural importance, forming one of the major economic centers within the region (EMTA).

In this deliverable initial work related to THESEUS Task 2.3 on Material Flow Analysis (MFA) and long-term projections (up to 2050) is presented. MFA is a well-established methodology, which allows for mapping and quantifying the flows of materials within a defined system. Within THESEUS, MFA is used to understand current resource use and to generate projection for their use in short, mid and long term and potentially until 2050. That comprehensive analysis will allow to identify spots where circular economy strategies could be implemented, thus facilitating the development of the closed loop systems of THESEUS H4C.

1.1 Purpose of the deliverable

The output of the T2.3 consists of three deliverables reflecting work progress at different timepoints of the project, where version 1 (current document) is due in M9, version 2 in M24 (November 2026) and the final version of the document in M36 (November 2027). The current report (version 1) aims at defining the THESEUS approach for MFA implementation within the project towards the Attica H4C and summarizes the work performed from the beginning of the project until M9. During that period, the focus was on structuring the work to be performed within the task and providing baseline methodology, while identifying interlinkages with other THESEUS tasks and deliverables. Based on discussions with partners initial use cases and sector of focus were identified and preliminary results obtained. This is reflected in this report, which serves as a starting point for further, more advanced work within T2.3.

1.2 Intended audience

The current version of the deliverable (v1) aims at structuring further work, defines the THESEUS approach and presents work, that is of ongoing status with some aspects still evolving. As a result, D2.7 is mainly intended for the THESEUS Consortium, especially the partners, who are involved in the task. This concerns the teams performing the MFA, but also partners, who are requested to provide data, and partners involved in the tasks using the T2.3 outputs. The objective is to present the final results in D2.9, which will be of interest to broader audience especially industries (particularly P4P but not exclusively), regional administration, policy makers and scientific community. It is worth noting, that the dissemination level of D2.7-9 is set to “public”. That makes it possible for anyone interested to follow the progress and assess the preliminary results at earlier stages.

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1.3 Structure of the deliverable and THESEUS context

This is the first out of three deliverables describing the work on Material Flow Analysis performed for THESEUS flows. The current document consists of seven sections. The first two sections introduce the reader to the MFA concept and how it is used in THESEUS project. That is followed by a section on MFA methodology, where the approach developed for THESEUS is presented including system definition and boundaries, data collection approach, THESEUS MFA model, and assumptions, limitations and data gaps explained. Section four describes the THESEUS MFA use cases, that were defined until now. Discussion section presents preliminary recommendations, challenges encountered and next steps towards the 2nd version of the deliverable, Broader context of THESEUS objectives is also considered.

It is worth mentioning that the MFA task of the THESEUS project is not a stand-alone task and forms a part of well-designed workplan, with different tasks that complement each other. Some of the outcomes, which are especially closely connected to T2.3 and receive/provide output include: KPIs definition for T2.4 and T2.5, analysis of sorting and upcycling processes based on T2.3 outcomes in WPs 4 and 5 and collaboration with T3.4, which analyses in flows in a logistics context.

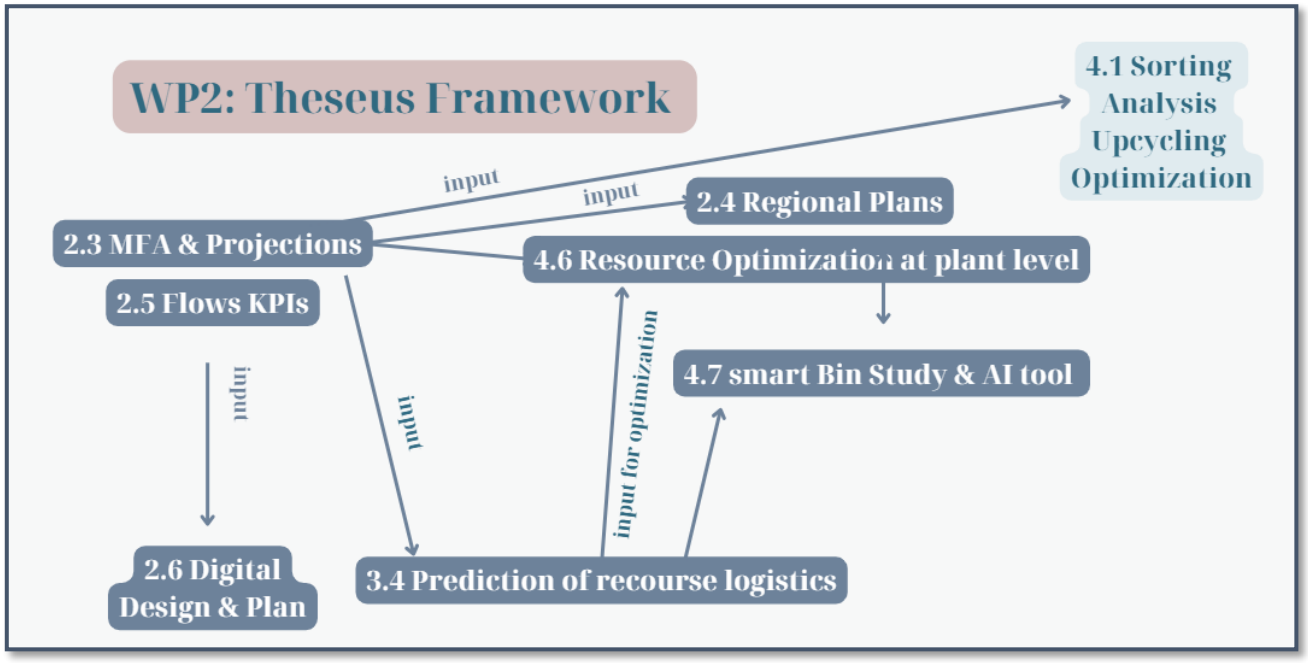


Figure 1 Links with other tasks

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2 Material flow analysis for Sustainable Waste Management in Attica

MFA is a well-recognized valuable tool, that can be used for detailed mapping of flows within a closed system. In Theseus MFA, is applied for the region of Attica for selected material, water and energy flows. Identifying, quantifying and analyzing the flows will provide comprehensive overview of the resource use. Further analysis will allow to identify hot spots and opportunities leading to resource use optimization. Strategies to address weak points will be formulated. Based on the results obtained future projections in the short, middle and long term will be developed for the region of Attica as well as for Greece, aligned with the general vision of EU and local authorities on waste management, recycling, reuse of solid waste and specific important flows such as recycling packaging (blue bin), textiles (purple bin), industrial waste and CDW, and proposing actions and strategies and policy guidelines (THESEUS Key Exploitable Result 23) to be adopted.

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3 MFA methodology and THESEUS approach

3.1 System definition and boundaries

The Material Flow Analysis (MFA) in THESEUS aims to capture the key material, energy, and water flows associated with selected circular value chains and systemic pilot actions implemented across the Attica region and beyond. The scope of the MFA is directly aligned with the project's ambition to monitor, simulate, and optimize circularity pathways for materials and resources of strategic importance.

In THESEUS, the MFA focuses on the following core flows:

- Textile waste from households, public and private collection systems, and reuse/recycling actors; (post-consumer textile waste)
- Recyclable Municipal Solid Waste (MSW) collected in theblue-bins[1] across Attica region, representing the separately collected waste packaging streams (paper, plastic, metal, etc.);
- Construction and Demolition Waste (CDW), including composite and wood fractions;
- Energy flows, with a focus on district heating, waste heat recovery, and integration of renewable energy sources (RES);
- Water flows, including non-domestic wastewater, reclaimed water, and stormwater, particularly as inputs to decentralised reuse and fertigation systems.

The system boundaries are defined as follows:

- Spatial boundaries include the urban, peri-urban, and industrial areas of Attica (the hub's core region), with extensions to peripheral demonstration regions, where applicable.
- Time boundaries include both the current baseline (pre-intervention) and future time steps, structured around the THESEUS demonstration phases and 2030–2050 circularity targets, defining the diverse but specific short-term (generally 2030 at the end of Theseus), mid-term and long term (potentially 2050) per case, sector/type and material.
- Process boundaries focus on the post-use phase of material flows — specifically from the point of waste generation (e.g. disposal by households, demolition activities, industrial discharge) through collection, sorting, treatment, and valorisation.
  While the MFA in THESEUS focuses primarily on the post-use phase, upstream production and use phases are considered where necessary to inform background assumptions — such as material composition, origin, or product lifespan — that improve the accuracy and clarity of flow modelling.

This approach brings together different sector interventions in a common model. It also makes it easier to compare flows and pilots and to run targeted simulations for each use case.

[1] In Attica blue bins are used for collection of source-separated packaging waste

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3.2 Data collection approach

The THESEUS MFA relies on a combination of **primary** and **secondary** data sources to quantify the selected flows and enable robust system modelling.

Primary data is collected from various sources across the THESEUS ecosystem and is governed by the project's data governance framework, which enables structured, transparent, and secure data sharing among a diverse set of stakeholders — including regional authorities, industrial partners, recyclers, technology providers, research institutions, and municipal actors involved in circular use cases**.**

To support the material flow modelling, structured questionnaires are distributed to partners managing specific flows — such as the recyclable MSW from the blue-bin system — to collect key data on input quantities, material composition, sorting performance, output streams, disposal methods, and basic operational parameters like energy use. Additionally, the Region of Attica, an important partner in the project, plays a key role in providing consolidated data from the National Waste Registry (Ηλεκτρονικό Μητρώο Αποβλήτων – Electronic Waste Registry), where available.

Last, to inform future scenarios and policy-aligned projections, the project draws on the Strategic Environmental Impact Assessment (Στρατηγική Μελέτη Περιβαλλοντικών Επιπτώσεων – SEIA) developed for the 3rd Revision of the Regional Waste Management Plan (ΠΕΣΔΑ) of the Region of Attica.

In parallel, the MFA integrates **secondary** data from:

- Scientific literature and technical studies;
- EU Projects dealing with material circularity, sorting, or industrial symbiosis;
- EU and country level statistical datasets
- Studies from EU Institutions, including the Joint Research Centre (JRC), Eurostat, and the European Environment Agency (EEA) — used to inform transfer coefficients, benchmarks, and policy-aligned indicators.

The **types of data** collected to support MFA modelling include but are not limited to:

- **Quantities of incoming and outgoing materials**, including monthly or annual volumes;
- **Material composition**, showing the share of different materials in each flow;
- **Sorting performance and output streams**, such as recovered materials and residues;
- **Final disposal methods and related costs**;
- **Basic operational data**, including working hours, throughput, and staffing;
- **Utility use**, such as energy and water consumption.

Where data gaps or inconsistencies are present, the modelling framework applies probabilistic estimation techniques and sensitivity analysis to ensure robust outcomes.

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3.3 THESEUS MFA model

3.3.1 The Process Simulation and Modelling (PSM) Tool

The development of MFA models and scenarios for the various streams examined in Theseus is based on the application of the Process Simulation and Modelling (PSM) tool, developed by TUC. The PSM tool has been extensively applied in various research projects, such as FACTLOG, PLOOTO, AQUASPICE and GREECE 4.0, to address large-scale modelling challenges inherent in regional circular economy modelling, going beyond the scope of a single industrial process or plant.

The PSM tool primarily focuses on modelling the various stages of individual processes, stages or value chains. In brief, core functionalities include:

- Material Flow Analysis, through the calculation of flows of different materials or energy across the individual processes, stages and value chains;
- Life Cycle Assessment, through the quantification of environmental impacts associated with a given product of the modelled process/value chain and the calculation of the corresponding used resources and generated pollutants;
- Assessment of Key Performance Indicators (KPIs) on Sustainability, Governance, Economy and Growth, such as carbon footprint, resource consumption, pollution, societal impacts as well as productivity growth, supply chain waste and customer satisfaction;
- Calculation of Sustainability Balanced Scorecards (SBSCs), to provide a measure for sustainability and circularity along the entire value chain based on selected KPIs.

The above functionalities have been extensively applied in various use cases. More specifically, the PSM tool has been utilized in the context of the PLOOTO project to model the value chains in industrial units and simulate individual processes providing digital twin capabilities, further used for the development of Digital Product Passports. The application has further included calculation of SBSCs, using PSM results from the modelling/simulation of individual processes to evaluate the overall performance of the supply chain. Furthermore, the PSM tool has been utilized in the AQUASPICE project as a part of the cyber-physical system controller for real time monitoring aiming to optimize water efficiency and closed-loop recycling practices.

Particularly for supporting Material Flow Analysis, the PSM tool provides a framework for building the "model" (i.e. the representation of the system and its processes) from the ground-up, with varying levels of detail when it comes to individual processes, processing units or MFA/LCA stages. As such, the tool is perfectly suited for defining the fundamental components of the analysis: processes (such as sorting of separated waste, upcycling stages, and landfilling) are treated as stocks, while materials are defined as flows between them. This modular and hierarchical structure allows mapping complex value chains for different streams, from the initial waste generation by consumers to the final uses or end-of-life for every material stream in the proposed (circular) system.

A key enhancement for this value chain MFA is the tool's capacity to incorporate the different actors involved in the value chain. This allows for a realistic representation of the complex interactions and material handoffs between stakeholders within the system boundaries. This detailed, multi-actor perspective is vital for accurately understanding and optimizing the flow of materials throughout the entire regional ecosystem.

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Within Theseus, the PSM is used for MFA modelling to provide analysis of different scenarios that include the linear 'As-Is' value chains with the proposed circular 'To-Be' solution(s) for the different waste streams. Mid-to-long-term scenarios for the PSM application will be built considering the assumption that the Theseus solution(s) for upgrading the value chain are massively applied to address the management of the whole waste stream.

3.3.2 Dynamic probabilistic material flow modelling

To address the dynamic nature and inherent uncertainties in THESEUS material systems, the project also applies the Dynamic Probabilistic Material Flow Analysis (DPMFA) method, originally developed by Bornhöft et al. (2016) and available as an open-source simulation framework in Python (dpmfa-simulator).

DPMFA extends traditional MFA by integrating time-based system behavior with probabilistic modelling techniques. This makes it particularly well-suited for simulating flows where both the volume of inflows and the distribution of materials across treatment pathways are uncertain or variable.

At the core of the model is a set of compartments, which serve as discrete building blocks representing different system units. These include:

- **Flow compartments**, where materials pass through without being retained;
- **Stock compartments**, where materials can accumulate and be released over time;
- **Sink compartments**, representing final destinations with no further outflow;
- **External inflows**, which introduce materials into the system (e.g. waste generation).

Material movements between compartments are governed by transfer coefficients, defined as probabilistic values to capture uncertainty. The model evolves over discrete time steps, with key outputs—such as flows, releases, and accumulations—calculated via Monte Carlo simulation. This approach allows the estimation of confidence intervals and statistical properties for each system variable throughout the simulation period.

By combining static structure with time-dependent probabilistic behavior, DPMFA enables the THESEUS MFA framework to simulate a wide range of material flow scenarios, test the impact of interventions, and assess uncertainty in key system parameters.

3.4 Assumptions, limitations, data gaps

At this early stage of THESEUS implementation, regional or national-level statistics are temporarily used to approximate local conditions, with the expectation that more detailed, pilot-level data will be integrated as demonstrations advance. Current limitations include incomplete data coverage across several material streams, variability in stakeholder engagement and data provision, and uncertainty regarding the scalability of proposed pilot interventions.

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4 THESEUS MFA use cases

This section introduces the THESEUS MFA use cases, which provide practical applications of the methodology to selected waste streams in the Attica region. Each sub-section presents: (i) the current practices and figures that define the baseline conditions, (ii) the design of the use case as developed within THESEUS, and (iii) preliminary or expected results. The focus is on three key sectors of strategic importance: textiles, construction and demolition waste (CDW), and recyclable municipal solid waste (MSW). Together, these use cases demonstrate how the Process Simulation and Modelling (PSM) tool and the Dynamic Probabilistic MFA (DPMFA) complement one another to capture the "as-is" situation and to simulate future circular scenarios.

4.1 Textiles sector

4.1.1 Textiles value chain in Attica – current practices and figures

The Attica region, which accounts for a substantial proportion of Greece's population and consumption, generates significant volumes of post-consumer textile waste. Current value chain practices remain largely linear and fragmented, characterized by limited infrastructure for separate collection, reuse, or recycling. Disposal through landfilling and incineration remains the dominant end-of-life pathway, with minimal reintegration of textile materials into circular loops.

Separate collection rates for textiles are currently low, despite the EU requirements for mandatory separate collection (introduced in Directive 2018/851). Collection schemes—such as those implemented through purple bins[2] or by civil society organizations—capture only a share of the total waste generated. At present, mechanisms such as Extended Producer Responsibility (EPR) are not yet operationally enforced, although foreseen in the national legislation since 2021 and introduced for textiles by the new amendment to the Waste Framework Directive, and thus obligations related to separate textile collection are not fully implemented.

Baseline data indicate that in 2019, approximately 7,800 tonnes of textile waste were diverted from landfill in the Attica region (Region of Attica, 2022). THESEUS targets a substantial increase in circular recovery, with an ambition to scale up to approximately 42,500 tonnes annually after 2030. This will be supported through a combination of proposed infrastructure upgrades, expansion of collection networks, and behavioral change interventions (e.g. larger network of purple bins, a fully functional and operational EPR scheme, the registration of textile producers to national registers, support consumer awareness and end-use capacities, taking into consideration and adjusting factors such as exports to other countries). For example, indicative as an assumption, automating 50% of the existing sorting capacity could yield up to a 30% increase in textile

[2] Purple bins are the dedicated collection infrastructure for post-consumer textiles in Greece. They are intended for the separate collection of clothing, footwear, and other textiles to enable reuse and recycling pathways.

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processing throughput, while the broader intervention package after 2030 is estimated to deliver greenhouse gas savings of approximately 155.7 tonnes CO_2-equivalent per year.

4.1.2 Use case description

The THESEUS textiles use case in Attica aims to demonstrate a replicable model for increasing circularity in post-consumer textile waste management by combining digital tools, infrastructure upgrades, and coordinated stakeholder engagement. The designed interventions target key inefficiencies in the current value chain, where textiles are predominantly disposed of in landfills or incinerated due to limited sorting capabilities and fragmented collection systems, as described above.

The use case introduces a semi-automated sorting line equipped with AI-powered fibre recognition and robotic handling systems. This system is designed to improve the identification and separation of textile fractions suitable for reuse, fibre-to-fibre recycling, and alternative upcycling routes. The deployment of this technology is complemented by the application of the Dynamic Probabilistic Material Flow Analysis (DPMFA) tool, developed and adapted by ICCS. The tool enables scenario-based modelling of textile flows, allowing projections of system performance under different policy and operational configurations.

The pilot will also integrate traceability features in line with emerging Digital Product Passport frameworks, enhancing data availability and transparency throughout the textile lifecycle. Engagement with municipal authorities, waste collectors, recyclers, and reuse organizations ensure that the initiative reflects real-world operational conditions and facilitates uptake of circular practices.

This integrated approach is expected to lead to a step-change in material recovery. By increasing sorting efficiency, improving the coverage of separate collection, and raising public awareness, the use case supports the THESEUS objective of scaling textile recovery in Attica from approximately 7,800 tonnes per year (baseline 2019, (Region of Attica, 2022).) to around 42,500 tonnes annually after 2030. In doing so, it also contributes to measurable reductions in greenhouse gas emissions and lays the foundation for replicability across other urban-industrial regions in Europe.

4.1.3 Preliminary results

Using the PSM tool, the MFA for post post-consumer textile waste was conducted for two different cases:

- An **"As-Is"** model was developed to map the current value chain, followed by
- A **"To-Be"** model designed to simulate technological enhancements and circular pathways that can be introduced by the THESEUS project.

The current THESEUS value chain for textile waste ("As-Is" Model)

The "As-Is" MFA model (presented in Figure 1) was developed to map and quantify the current state of the post-consumer textile waste value.

Based on data from the year 2023, the total textile waste that was separately collected was equal to about 7,000 tonnes. Once collected, the material undergoes a basic sorting process with limited outcomes. Separately collected textiles are manually sorted as follows a): a small fraction of very good-quality items is reused through charity donations; b) an equally small fraction is recycled towards textiles used in industries; c) and a small residual fraction of 2% comprising of non-textile contaminants and textiles unfit for reuse is

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discarded and follows the management “path” of all mixed solid waste. The largest part of the remaining post-consumer textiles is exported for further processing (mainly recycling or reuse). The critical limitation of the "As-Is" model is the lack of more automation as the inability to sort textiles by fiber type prevents high-value recycling and results in an almost linear flow where resources are lost to the Greek economy through export to other markets.

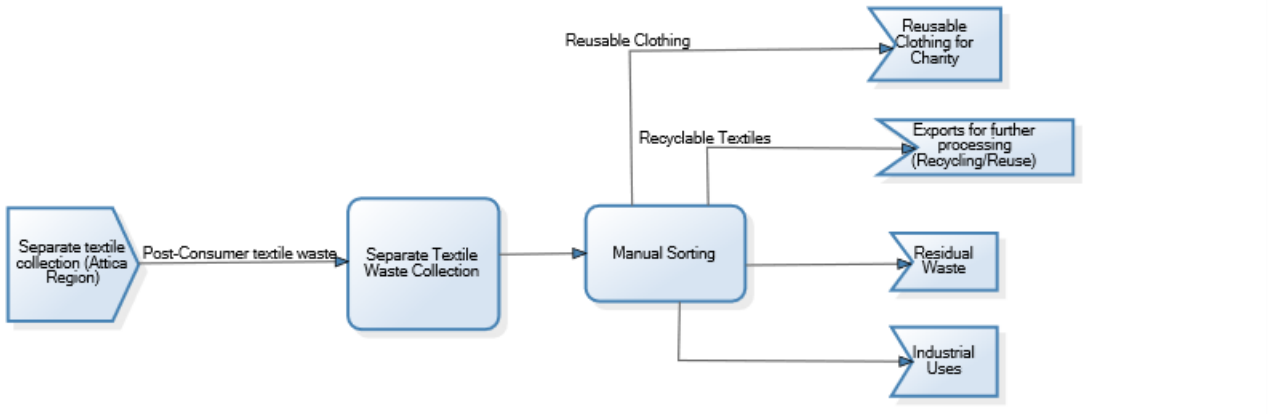


Figure 2: The 'As-Is' MFA model, as developed in the PSM tool

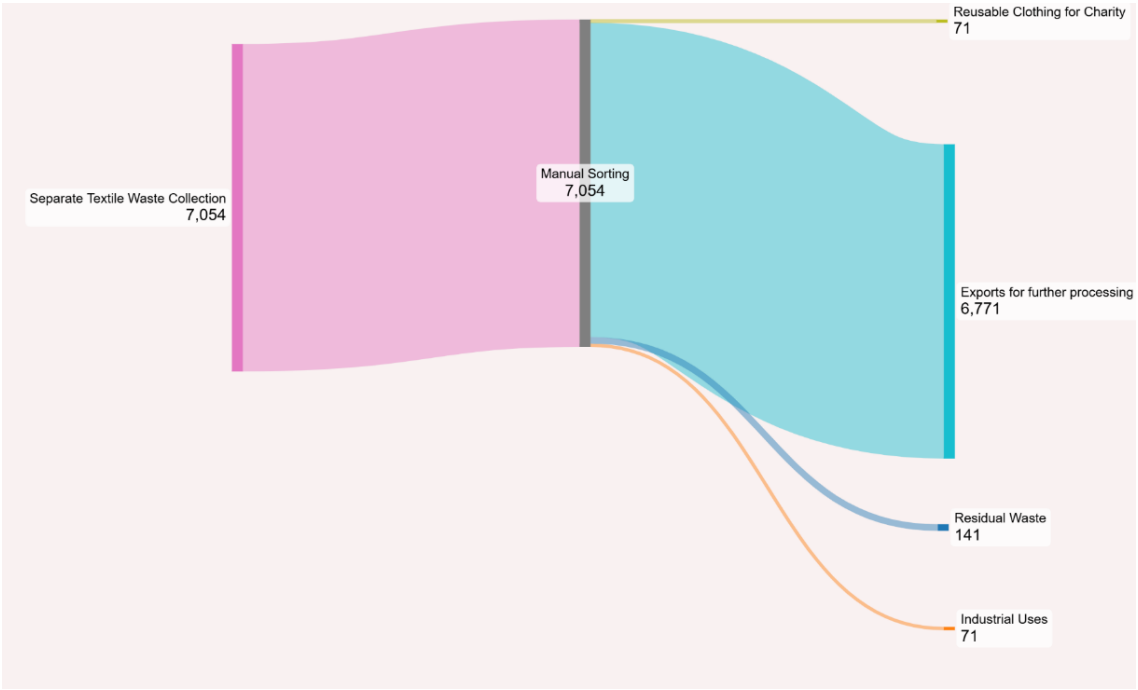


Figure 3: Results of the “As-Is” model MFA (quantities in tn/year)

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A first snapshot of the Theseus value chain ("To-Be Model") and the initial version of the relevant model is visualized in Figure 4. It builds directly upon the "As-Is" model by utilizing the same initial assumptions and values for the textile input stream. A key element of this advanced value chain is the introduction of automated sorting for the collected post-consumer textile waste. The specifications of this, as well as the entire system, are currently under development by the ICCS, considering the required characteristics of output streams, as well as the requirements of the end-uses.

For the purposes of the preliminary modelling presented in this Deliverable, we have assumed that the sorter's performance mirrors that of a recent study (Du et al., 2022), segregating input textiles into 14 distinct categories, further assuming an average composition of the incoming post-consumer textile waste. For this preliminary phase of the model, a clear logic is applied to route these streams:

- All quantities of natural fibers (Cotton, Wool, Silk, Viscose) are directed for Chemical Treatment & Respinning , a processing stage, currently under testing and development by the University of Huddersfield;
- The pure Polyester stream can undergo depolymerization, a processing stage developed by CIRCE and subsequently used to produce rPET;
- The remaining streams, which include mostly blended fibers (e.g., Polyester/Cotton, Nylon/Spandex) as well as textiles of various compositions, are directed towards various **open-loop recycling processes**.

It is evident that such, more precise, sorting would unlock previously unavailable valorization processes, within the boundaries of the local economy.

For this preliminary model, it is assumed that the output regarding the products of the Open loop recycling is split to 45% to produce filling materials, 45% to produce insulators, and 10% to develop innovative reinforcing agents for construction materials.

The above distribution is a working assumption that will be further elaborated during the project and finalized in subsequent versions of the deliverable, based upon the capacity and characteristics of the developed technologies and the requirements of the corresponding end-users.

Indicative results regarding material flows are presented in **Error! Reference source not found.** while Figure 6 portrays the main differences in output between the 'As-Is' and the 'To-Be' models.

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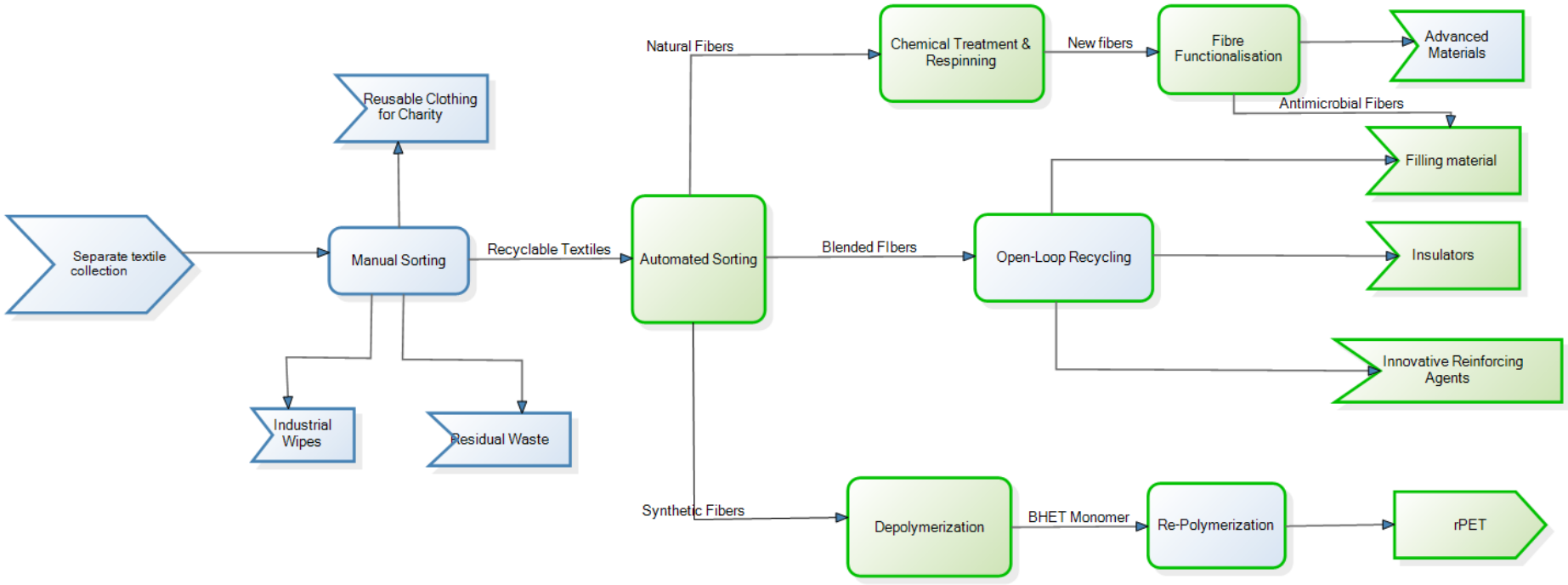


Figure 4: The 'To-Be' MFA model, as developed in the PSM tool

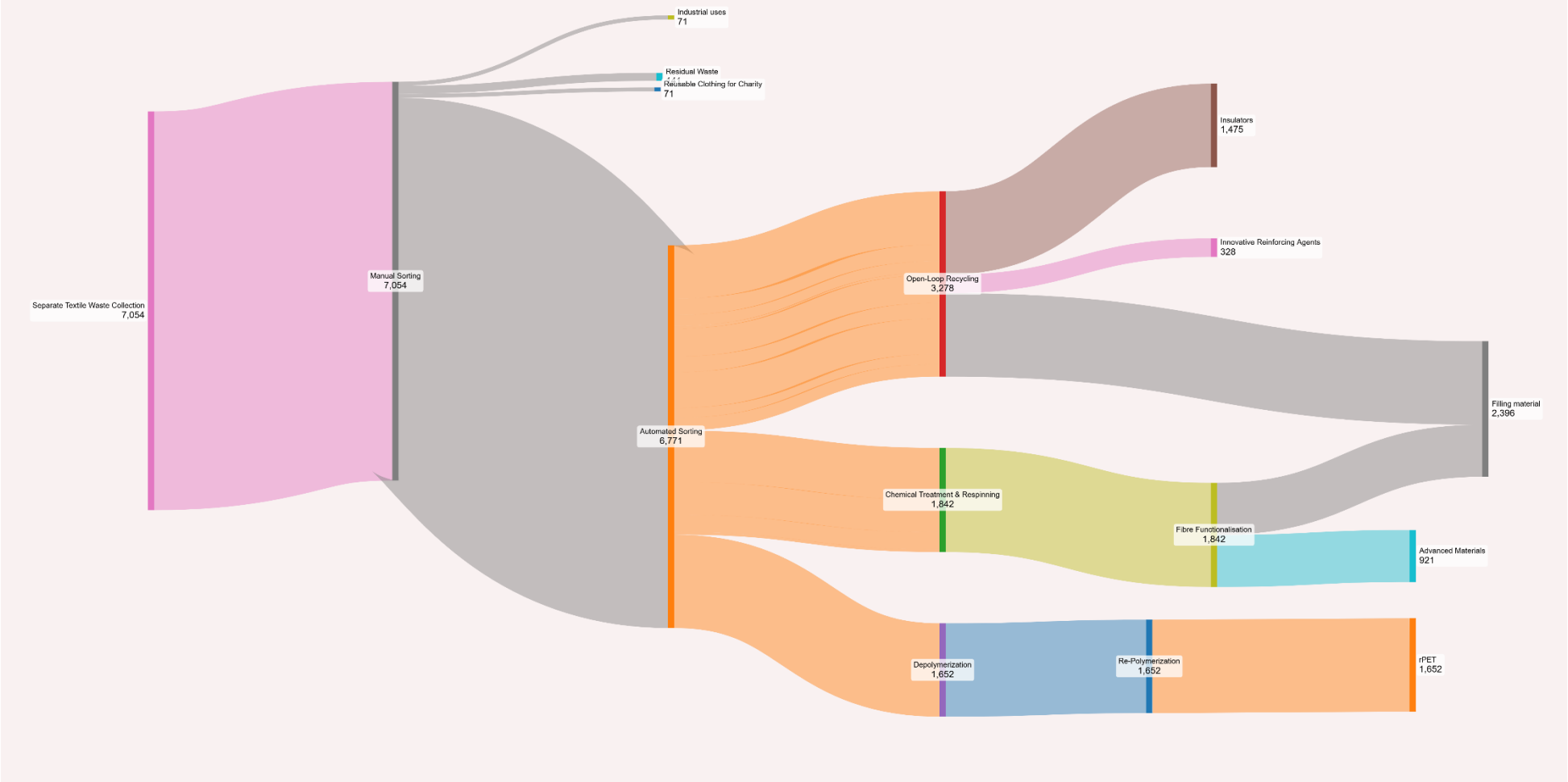


Figure 5: Sankey diagram of the 'To-Be' MFA (quantities in tn/year)

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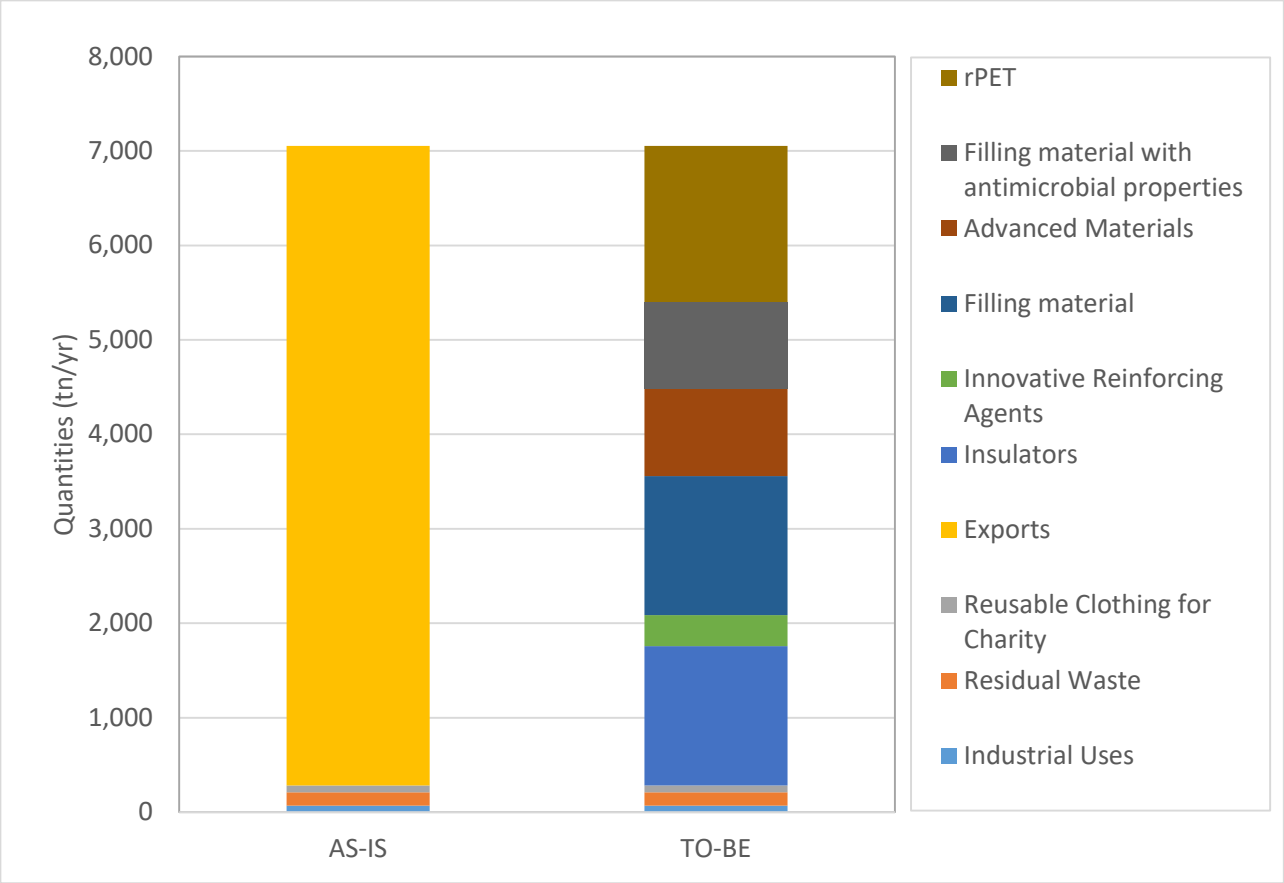


Figure 6: Comparison of key material outputs for the 'As-Is' and 'To-Be' scenarios

Based on the preliminary "To-Be" MFA model, the proposed final end-products from the open-Loop recycling of the blended fibres are estimated to be **1,842 tonnes** for the production of filling materials, **1,475 tonnes** for the production of insulators, and **328 tonnes** as innovative reinforcing agents. For the purpose of this model , and under continuous testing to assess and validate the suitability of each material for each use, these newly produced materials will be tested by the Theseus industrial end users.

As assumed above and assuming full-scale application of the Theseus technologies, natural fibre streams are directed towards chemical treatment & respinning, where the advanced process regenerates them into two equally split end-products (each equal to **921 tonnes)** : the new fibers that undergo fibre functionalisation to create high-value advanced materials and the fibers with antimicrobial properties with potential application for the production mattresses. The addition of the fibres with antimicrobial properties and the blended fibres from the open-loop recycling provides an estimated total of **2,396 tonnes** that can be utilized as filling material.

Finally, the polyester streams can undergo depolymerisation to produce the BHET monomer which subsequently can be used towards the production of rPET. The work undertaken within the framework of Theseus is experimental and aimed at providing proof-of-concept for this recycling pathway. This research will validate the process and generate the essential data on yield and purity, laying the foundation for a future, scaled-up industrial scenario. In the 'To-Be' model we readily assume that the final end product from this process is high-quality rPET, a material with significant industrial value for applications like thin films and multilayers. Therefore, it is assumed that the BHET monomer produced can be further processed via re-polymerization (polycondensation) to create virgin-quality rPET pellets. These rPET pellets, based on the calculations of the model will amount to **1,652 tonnes** per year.

To better visualize the critical shifts in the value chain, Figure 6 provides a focused comparison of the key output streams between the two models. This allows for a direct contrast between the low-value exports that dominate the 'As-Is' model and the new, high-value materials created in the 'To-Be' model.

The "To-Be" model fundamentally redesigns the regional textile economy, having the potential to create a closed-loop recycling system that transforms local waste into high-value secondary raw materials. The implementation of these interventions leads to the calculation of fundamental Key Performance Indicators (KPIs).

This model quantifies the environmental impact of the THESEUS interventions by calculating the total 'avoided CO2 emissions'. This key performance indicator is based on the principle of material substitution, where it is assumed that the new products substitute the production of an equivalent amount of virgin materials. For this preliminary assessment, the most probable virgin material candidates to be substituted have been identified based on current market applications. The associated carbon footprints have been derived from review of the relevant LCA literature and are aimed at providing an initial basis for preliminary assessments, subject to further literature screening and review.

- Filling Material replaces virgin Polyester Staple Fibers (PSF), which has a carbon footprint of 3.46 tn CO_2/tn (Li et al., 2024).
- Insulators replace virgin Glass Wool, with an estimated carbon footprint of 1.125 tn CO_2eq/tn (Grazieschi et al., 2021).
- Reinforcing Agents replace virgin Polypropylene fibers, with a carbon footprint of 1.58 tn CO_2eq/tn (Alsabri et al., 2021).
- Functionalized Fibers replace virgin Cotton, which has a carbon footprint of 4.7 tn CO_2eq/tn (Kalliala & Nousiainen, 1999).
- rPET Pellets replace virgin PET, which has a carbon footprint of 2.23 tn CO_2eq/tn (The Association of Plastic Recyclers, 2020).

By multiplying these carbon footprint emission factors with the quantity of each virgin material to be replaced a preliminary analysis shows that a total of **18,480 tonnes** of CO2 equivalent can be annually avoided.

For the **entire Attica region**, THESEUS will expand the modelling of the textile waste stream beyond the pilot sites. The current “As-Is” mapping developed with the **Process Simulation and Modelling (PSM) tool** has provided a first quantitative picture of the existing value chain. Building on this, the next phase will integrate the **Dynamic Probabilistic MFA (DPMFA) tool**, adapted to Greek regional conditions.

The PSM-based model delivers a process-oriented representation of current flows and allows for comparative scenario building (e.g. As-Is vs To-Be). The DPMFA will complement this by introducing **time-dependent modelling, probabilistic treatment of uncertainties, and long-term projections**, enabling the analysis of circularity trajectories under different policy and technological assumptions. Together, these two approaches provide both a **detailed operational snapshot** and a **forward-looking, uncertainty-aware perspective**, strengthening the basis for planning textile waste management strategies in Attica.

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4.2 Construction and demolition waste

4.2.1 CDW in Attica – current practices and figures

Construction and demolition waste (CDW) constitutes one of the most significant and resource-rich waste streams in the Attica region. In 2019, approximately 997,742 *tonnes* of CDW were collected. However, the current recycling and reuse rate is estimated at only 30–35%, with the remainder often disposed of in landfills or used in low-value recovery applications. (Region of Attica, 2022).

The CDW stream in Attica includes substantial quantities of recoverable materials, such as metals (up to 11.3% in Southern European contexts), wood, and glass. Key challenges include limited on-site separation, bulk handling of mixed waste, and inadequate traceability—especially in small-scale construction and renovation projects.

To validate and enrich these figures, official confirmation of CDW quantities and composition has been requested to the Attica region authorities, while access to operational data that can support more precise modelling is also to be explored.

THESEUS aims to address current inefficiencies by integrating adaptive sorting technologies for high-value CDW fractions and developing process-level material flow models. The regional objective is to increase the CDW recycling rate to at least *50%* by 2030.

4.2.2 Use case description

To be updated in the next versions.

4.2.3 Expected preliminary results

To be updated in the next versions.

4.3 Recyclable Municipal Solid Waste

4.3.1 Recyclable municipal solid waste in Attica – current practices and figures

The THESEUS pilot targeting recyclable municipal solid waste (MSW) focuses on improving source separation and sorting efficiency, with an emphasis on packaging materials collected via blue bins, as well as recyclable fractions embedded in mixed MSW streams. In 2019, 81,351 tonnes of packaging waste were collected through blue bins in Attica. However, high contamination rates have led to poor recycling outcomes (Region of Attica, 2022).

The pilot will rely on an **automated sorting system** capable of separating plastics, metals, paper, textiles, and biobased materials. These innovations will be supported by traceability and modelling tools developed within THESEUS. More detailed insights will be drawn from stakeholder data; a questionnaire has been distributed to **WATT / GEOCYCLE**, and results will inform the next phase of the MFA model. A copy of the questionnaire is provided in the **Annex** of this deliverable.

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The overarching objective is to **increase the recovery of plastics and packaging by 20–30%**, thereby reducing the share of recyclable materials that are currently lost to landfill. This improvement will be achieved through technological upgrades, better system integration, and closer alignment with circular economy objectives in the region.

4.3.2 Use case description

To be updated in the next versions.

4.3.3 Expected preliminary results

To be updated in the next versions.

5 Discussion

5.1 Preliminary recommendations

To be updated in the next versions.

5.2 Challenges encountered and strategies to address them

A significant challenge encountered in the implementation of the THESEUS MFA framework at this stage relates to **data availability and quality**, particularly in defining consistent and granular inputs across waste streams and regions.

For **textiles value chain**, while the European Union has mandated separate collection by 2025 under the revised Waste Framework Directive, available data on textile flows remains fragmented. According to the Joint Research Centre (JRC), there are still no harmonized definitions or robust tracking mechanisms across Member States for textile waste, especially for post-consumer apparel, footwear and home/interior textiles. Consequently, THESEUS has prioritized **post-consumer textile waste** as the core focus of its first implementation phase. This aligns with both European guidance and waste generation trends (currently assumptions based on literature, while a relevant study by the national recycling organization on the composition of recycling materials in blue bins is pending to be published and to be taken into consideration) in the Attica region.

For **construction and demolition (C&D) waste**, a major bottleneck lies in accessing site-level and treatment data, which is typically dispersed across municipalities and treatment operators. To overcome this, the THESEUS team has initiated **direct engagement with Attica regional authorities** to access operational data and identify suitable pilot sites. These interactions are ongoing, and data obtained will feed into the next iteration of the MFA model for CDW.

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5.3 Next steps and strategic vision

The preliminary results presented in this deliverable establishes the first basis for the development of MFAs models across the project. Subsequent versions of the model will be enhanced to provide more granular, data-driven, and comprehensive analysis. The key next steps are as follows:

- The **development of MFA for CDW and packaging waste streams**, where the collection of data to cross-check and validate existing baselines is currently underway.
- **The expansion of the suite of Key Performance Indicators (KPIs)** through the THESEUS Task 2.5 to introduce specific circularity indicators to more comprehensively quantify the environmental, economic, and social effects of THESEUS interventions.
- **The transition from a literature-based model to a fully data-driven approach** by integrating primary data from the extensive technical questionnaires distributed to project partners, including both industrial end-users and research laboratories.
- **The development of a detailed scenario assessment** to evaluate the impact of different technological choices, collection rates, and processing capacities within the Attica region, providing a robust analysis of potential future pathways.
- **The refinement and completion of the mapping of the entire value chains**, including all intermediate processes and final products, to create a more accurate representation of the material flows.
- **The enhancement of the robustness of the environmental impact assessment.** The subsequent MFA model, informed by primary data, will account for the carbon emissions of THESEUS innovations (e.g., energy consumption of sorting and recycling). This will allow for the calculation of a **net annual CO_2 saving** (avoided virgin production emissions minus new process emissions), providing a more realistic and comprehensive assessment of the project's climate benefits.

6 Conclusions

To be elaborated in the next versions.

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Annexes

Annex 1 Questionnaire to WATT

THESEUS Hub4Circularity

Ερωτηματολόγιο για την επεξεργασία αποβλήτων στο ΚΔΑΥ της WATT στο Κορωπί

ΠΕΡΙΕΧΟΜΕΝΑ

Ενότητα 1: Γενικές Πληροφορίες και Περίοδος Αναφοράς 3
1. Περίοδος Αναφοράς 3
2. Κύριο Πρόσωπο Επικοινωνίας στην WATT για αυτό το αίτημα δεδομένων 3
Ενότητα 2: Πληροφορίες για το εισερχόμενο ρεύμα αποβλήτων 3
3. Συνολική Μέση Μάζα Εισερχόμενων Μεικτών Αποβλήτων 3
4. Μέση Σύνθεση Εισερχόμενων Μεικτών Αποβλήτων (σε Ποσοστό κατά Μάζα) 3
5. Μέση Περιεκτικότητα (%) σε Υγρασία των Εισερχόμενων Μεικτών Αποβλήτων: 5
Ενότητα 3: Απόδοση Διαλογής & Ρεύματα Εκροών 5
6. Διαχωρισμός ανακυκλώσιμων υλικών (τόνοι/ημέρα): 5
7. Μάζα Ρεύματος Μη Ανακυκλώσιμων Υπολειμμάτων / Απορριμμάτων (προς τελική διάθεση) 5
8. Ανάλυση Μεθόδων Τελικής Διάθεσης 5
9. Κόστος Τελικής Διάθεσης 6
Ενότητα 4: Λειτουργικές Παράμετροι 6
10. Ώρες Λειτουργίας 6
11. Μέση Πραγματική Ροή Υλικού (Average Throughput Rate): 6
12. Κατανάλωση Ενέργειας: 6
13. Κατανάλωση Νερού 7
14. Ανθρώπινο Δυναμικό 7
15. Χρόνος Διακοπής Λειτουργίας για Συντήρηση (Downtime) 7
Ενότητα 5: Πρόσθετες Πληροφορίες 8

2

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