ForestPaths

Co-designing holistic forest-based policy pathways for climate change mitigation

D4.2 Report on improved methods and tools

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Partner(s): VITO, EFI

Author(s): Amelie Müller, Timokleia Orfanidou, Gustavo Ezequiel Martinez, Janne Järvikylä, Giuseppe Cardellini

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Key take-away messages

- The *bw_timex* tool is a newly developed open-source library for time-explicit life cycle assessment (LCA), which combines prospective and dynamic life cycle assessment.
- *bw_timex* is the only one-stop-shop software available to perform prospective and dynamic LCA altogether and can be used to evaluate any system over time, including but not limited to wood-based materials.
- *The aiphoria tool* is a newly developed open-source software library for assessing dynamically wood material flows and its associated carbon stocks and stock changes.
- *aiphoria* enables and simplifies the assessment of both the material flows and temporary carbon storage of the wood products' supply chains.
- *aiphoria* is flexible in terms of spatio-temporal resolution and system representation (e.g. process or product-based)
- *bw_timex* and *aiphoria* provide a software platform for a next generation assessment of the role of Forest-based bioeconomy in climate change mitigation.

Summary

This deliverable presents the results of the performed improvements on the methods and tools for quantifying the mitigation potential of forest-based products.

Firstly, it presents the open-source software library *bw_timex,* which enables time-explicit life cycle assessment (LCA), which combines prospective and dynamic LCA. Time-explicit LCA is a first-of-its-kind software implementation for a comprehensive evaluation of the life cycle impacts of products over time by accounting for temporal changes at the inventory and impact assessment step in LCA. It is integrated in the popular LCA software framework *brightway* and can be applied to any product system given its generic structure. It is highly useful for substitution assessments in the wood-based industry as it can account for temporal changes across the supply chain of the wood-based and alternative materials as well as temporal dynamics in emissions, such as biogenic carbon uptake and release.

Secondly, the deliverable presents the open-source software library *aiphoria,* which allows the assessment of wood material flows and its associated carbon stocks and stock changes over time. *aiphoria* is specifically developed to facilitate wood flow assessment, which can support Tier 3 methods by employing ‘stock-change’ or ‘production’ approaches outlined in the IPCC 2019 guidelines for Harvested Wood Products.

The two software are meant to be coupled following a soft-link approach to assess the role of the forest-based bioeconomy in climate change mitigation. *aiphoria’s* results will provide information on the structure of the EU wood supply chain and the amount of wood used in each product category. This data will be used, among others, to scale-up the product-level substitution factors (CO_2 saving per volume of wood in product *w*) developed with *bw_timex* at continental scale (total volume of wood consumed for product *w* in the whole EU multiplied by its substitution factor) to obtain the EU-level substitution potential.

List of abbreviations

Abbreviation	Explanation
bw_timex	TIMe-EXplicit LCA in brightway
CBS	Climate- and Biodiversity-Smart
EoL	End-of-life
EU	European Union
GHG	Greenhouse gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MFA	Material Flows Analysis
ODYM	Open Dynamic Material Systems Model
SWE	Solid Wood Equivalents
VAM	Value Added Market
StdDev	Standard Deviation
lt	Lifetimes
RoW	Rest of the World

1 Introduction

The goal of the ForestPaths project is to provide clear policy pathways that outline alternative trajectories for how European forests and the forest-based sector can help climate change mitigation, while conserving their biodiversity and sustaining ecosystem services. This overall goal will be achieved by: improving the understanding of forest practitioners' decision-making behaviour on Climate- and Biodiversity-Smart (CBS) forest management; develop monitoring methods for climate change-related risks from forest disturbances; assemble a next-generation integrated assessment framework; co-design, quantify and evaluate holistic forest-based policy pathways; maximise impacts by fostering collaboration and facilitating knowledge exchange.
In this framework, WP4 develops enhanced tools, databases and methods to better estimate the mitigation potential and biodiversity impact of the European forest-based bioeconomy, including the substitution and carbon storage effect of forest-based material and energy products, with appropriate time dynamics.

This deliverable reports on the work in Task 4.2, which entails the creation of a tool platform for improved quantification of the mitigation potential by the forest-based sector. More specifically, this deliverable reports on two distinct methodological and technical improvements. The first enhances the open-source software capacity of Life Cycle Assessment (LCA) (T4.2.1), which will be used in Task 4.3 to develop the substitution factors of the forest-based materials that takes into account the spatio-temporal variability of the sector. This work has produced the open-source software package *bw_timex* that links existing open-source LCA software *premise, temporalis* and *brightway*, allowing for a joint usage of the individual software capabilities to include temporal dynamics and future technological changes into LCA and substitution assessment analysis.
The second work improves the modelling of temporary carbon storage in wood products (T4.2.2). This work has developed the open-source software package called *aiphoria* that allows for dynamic wood material flow modelling and assesses the relative carbon storage effect.

The two software are meant to be coupled following a soft-link approach to assess the role of the forest-based bioeconomy in climate change mitigation. *Aiphoria's* results will provide information on the structure of the EU wood supply chain and the amount of wood used in each product category. This data will be used, among others, to scale-up the product-level substitution factors (CO_2 saving per volume of wood in product *w*) developed with *bw_timex* at continental scale (total volume of wood consumed for product *w* in the whole EU multiplied by its substitution factor) to obtain the EU-level substitution potential.

In the remainder of the report, the specific issues the two tools solve will be presented together with an explanation of their main features and characteristic.

2 bw_timex

2.1 Background

Life cycle assessment is an established method to assess the environmental impacts of products and services (Sala et al. 2021). LCA is also the method used to assess the substitution potential of wood and wood-based products (Leskinen et al. 2018). This is done by comparing the life cycle greenhouse gas (GHG) emissions of the wood product and its functionally equivalent fossil-based alternative. The life cycle of wood products typically covers multiple decades, including the tree growth, harvest, processing, first use application and potential cascading use. Conventional LCA methods do not consider temporal dynamics over the lifetime of products by assuming static, simultaneously occurring processes. Two advanced LCA methods consider certain temporal dynamics: 1) dynamic LCA considers explicitly the timing of processes and emissions, with tools such as *temporalis* (Cardellini et al. 2018), allowing to know precisely when in time impacts, or benefits, takes place. 2) prospective LCA, done with tools such as *premise* (Sacchi et al. 2022), models LCA databases at a future point of time, allowing to know how future changes will affect the supply chain of the system under study and, in the case of wood products, if and how they will affect the substitution potential of wood products. A full consideration of temporal dynamics in a single method is lacking in LCA and, as consequence, in the assessment of the substitution benefit of wood products. Such a combined method is required to better assess the substitution benefit of wood products and help developing more targeted policies that can take into account not only the order of magnitude of the substitution effect but also when it is exerted and how it evolves over time in light of our societal and technological changes.

In the project, we coped with this research gap by developing a method to combine the two LCA methods that resulted in the open-source software *bw_timex* that will be presented in the next sections.

2.2 Software

The developed open-source software tool *bw_timex*[1] allows to assess the environmental impacts of products and processes over time with a full consideration of temporal dynamics by combining prospective and dynamic LCA approaches, see Figure 1. The method enhances the LCA stages life cycle inventory (LCI) and life cycle impact assessment (LCIA). This includes 1) tracking the timing of processes, 2) selecting the variable or evolving production technologies at this point in time at the LCI stage and 3) taking into account the timing of emissions the LCIA stage.

[1] https://github.com/brightway-lca/bw_timex

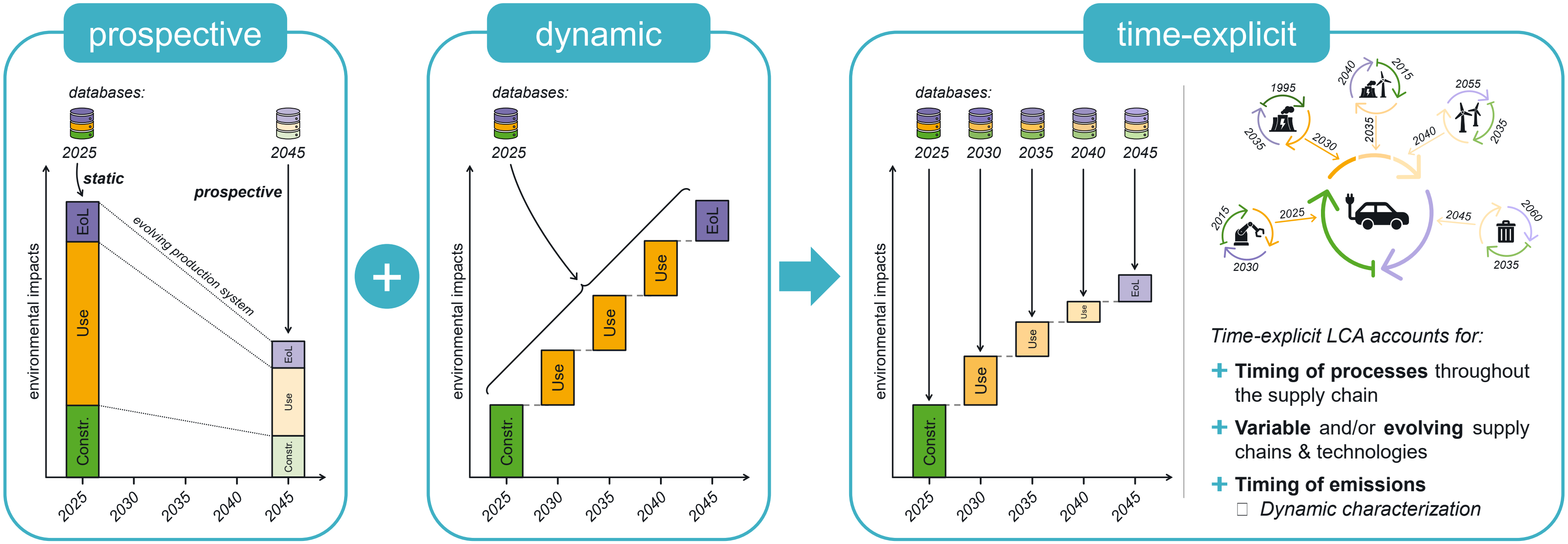

Figure *1*: Schematic representation of time-explicit LCA as a combination of prospective and dynamic LCA. EoL = End-of-Life

While *bw_timex* can be used to assess the substitution potential of wood-based products - an application for which the assessment of temporal dynamics of the system is highly relevant -, it has been developed as a generic method that can be used to assess any product system at any type of temporal resolution. This universality and temporal flexibility make *bw_timex* a useful tool for the entire LCA community.

2.2.1 Software integration

bw_timex is an open-source (BSD 3-clause) python package, readily available to install via *pip* or *conda*. Its source code is hosted on Github[1] and the documentation can be found under readthedocs[2].

It is developed as part of the *brightway* LCA ecosystem, which has the following advantages.

- Alignment in data structure has been ensured. As such, *bw_timex* can be easily applied using common LCA databases, such as ecoinvent, through the ecoinvent import functionalities of *brightway.*
- Interoperability with the other tools and assessment methods of the *brightway* LCA ecosystem is given, allowing users to combine a time-explicit LCA assessment quickly with other LCA investigations in a multi-step analysis.
- Increased user friendliness of the tool and maximization of the potential uptake by LCA practitioners.

bw_timex integrates functionalities from the open-source LCA software *temporalis* for dynamic LCA and *premise* for prospective LCA. Premise is a Python tool for prospective life cycle assessment that allows users to project the ecoinvent 3 database into the future, using scenarios from Integrated Assessment Models (IAMs). It does so by modifying the ecoinvent database to reflect projected energy policy trajectories, include emerging technologies, modify market shares as well as technologies' efficiency. For ForestPaths, *premise* is used to modify the LCI database used to develop the substitution factors based on the results of the IMAGE model. Figure 2 shows the linkage of *bw_timex* with these tools: *Premise* can be used to generate the background databases for specific time-steps, e.g. future versions of the LCI database ecoinvent that reflects changes in the technology landscape that are compatible with potential wider socio-economic and climate-policy development. Alternatively, users can also provide custom-generated prospective databases if adhering to a similar data structure. The foreground system can be modelled in *brightway* or imported from other LCA software. During the calculation steps within *bw_timex*, which are described in the next section in detail, the graph traversal algorithm of *temporalis* and LCA and LCIA calculation methods from *brightway* are used. The output of *bw_timex* is described in the next section.

[2] https://timex.readthedocs.io/en/latest/

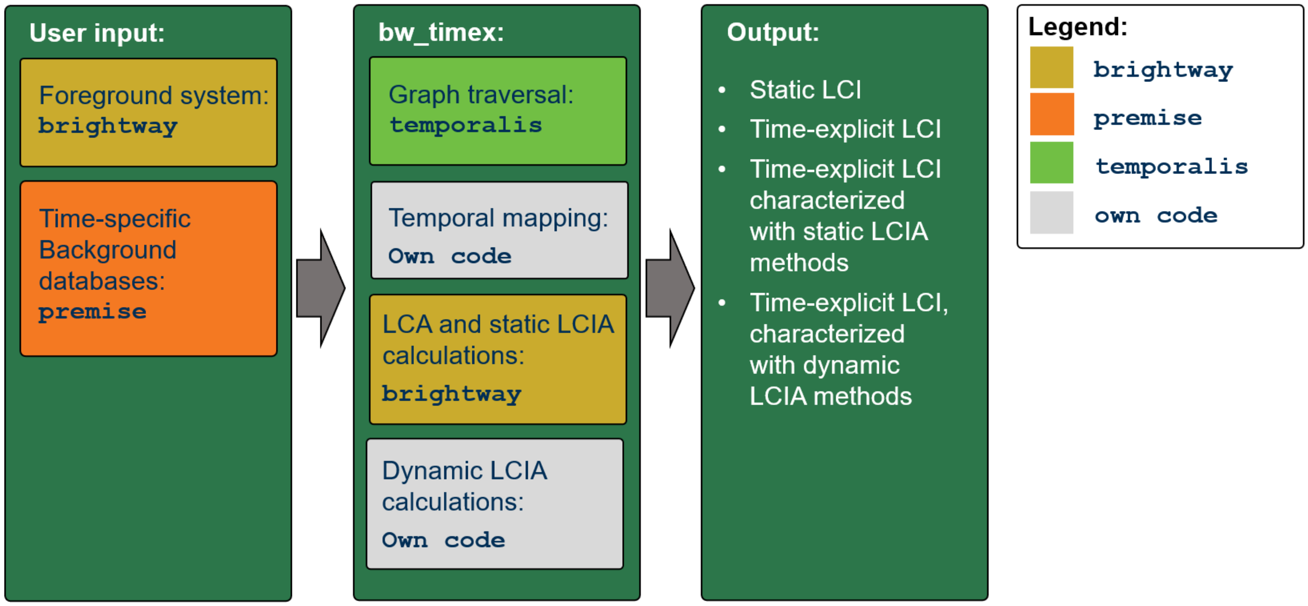

Figure *2*: **linkage of existing LCA software in bw_timex**

2.2.2 Method

The following section provides a general overview of the method. A complete description is found in its online documentation[3], including detailed descriptions of the tool's theory[4], installation instructions[5], documentation of functionalities[6], and two thoroughly documented, step-by-step tutorials with interactive jupyter notebooks[7].

The workflow of *bw_timex* can be grouped in six steps: 1) user input, 2) graph traversal, 3) time mapping, 4) inventory calculation, 5) static impact assessment and 6) dynamic impact assessment, as shown in Figure 3 and briefly described below.

[3] https://docs.brightway.dev/projects/bw-timex/en/latest/#
[4] https://docs.brightway.dev/projects/bw-timex/en/latest/content/theory.html
[5] https://docs.brightway.dev/projects/bw-timex/en/latest/content/installation.html
[6] https://docs.brightway.dev/projects/bw-timex/en/latest/content/api/index.html
[7] https://docs.brightway.dev/projects/bw-timex/en/latest/content/examples/index.html

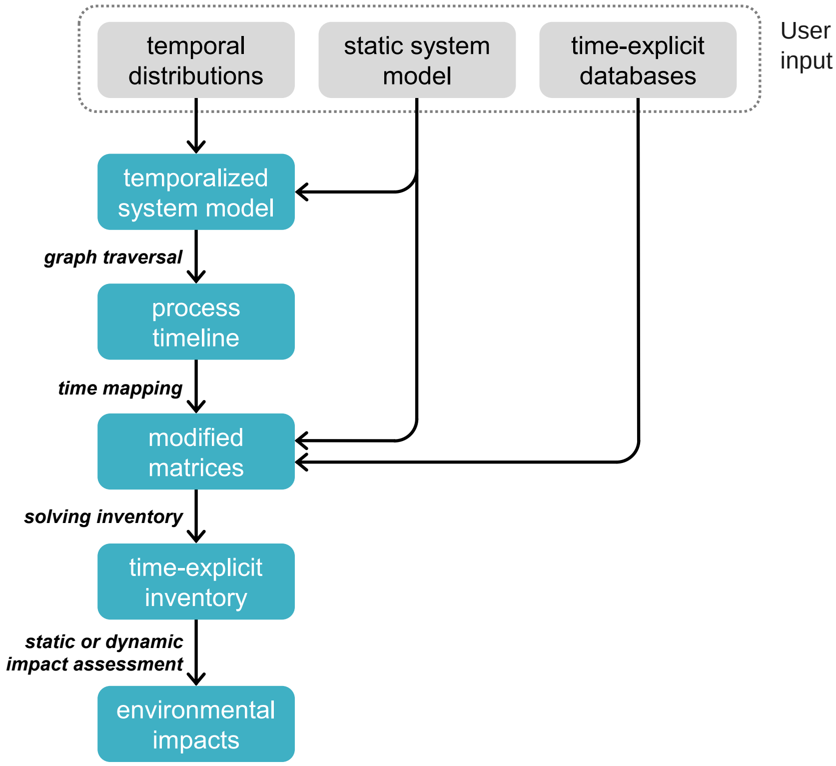

Figure 3: Flowchart of *bw_timex*

2.2.2.1 User input

The user needs to provide the LCI of the product/system under study, often also called foreground system. In the case of a substitution analysis for wood products, the LCI consists of the wood-based product and its fossil alternatives. For any input or emission in this system, temporal information in the form of a 'temporal_distribution' can be added. This temporal information describes the temporal relationship between production and supply of this input, e.g., that a material is produced 2 years before it is used. The temporal information is an optional input with a high format flexibility for different use cases, including different types, such as relative or absolute time, and flexible temporal resolution. Lastly, the user also needs to provide a set of background databases, which must have a reference in time.
A detailed description of the required format of the user input is given in the online tutorials.

2.2.2.2 Graph traversal

The graph traversal algorithm from *temporalis* is used to propagate the temporal information of each node along the supply chain. As in Temporalis, the supply chain graph is traversed starting from the functional unit. At each process, the graph traversal uses convolution to combine the temporal distributions of the process and the exchange it consumes into the resulting combined temporal distribution of the upstream producer of the exchange. An example of a convolution of two simple temporal distributions is given in Figure 4.

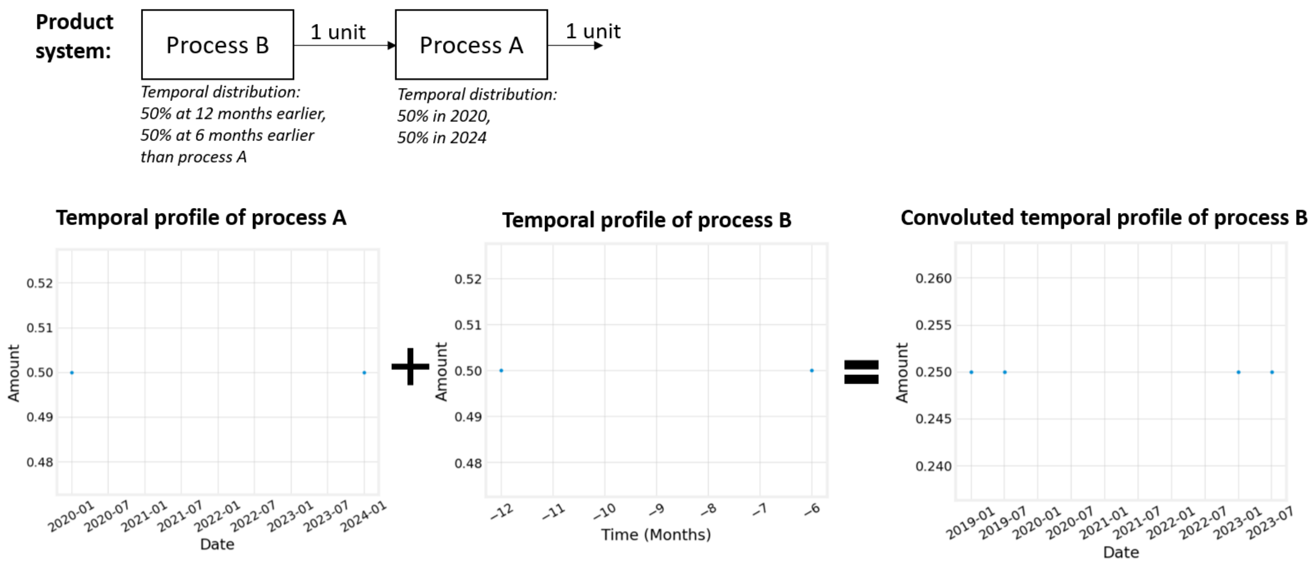

Figure 4: convolution of two simple temporal distributions

The traversal is priority-based, meaning that each exchange is evaluated for how much of the maximum possible LCA score it (could) contribute, with the most (potentially) damaging exchanges being evaluated first. The traversal through the supply chain continues until either the impact of a particular exchange falls below the cutoff criteria (by default, 0.1% of the total possible impact), or until the maximum number of traversal steps has been reached (by default, 10.000). It is possible to also lower the cut-off numeric criteria to make sure we aren't prematurely excluding any supply chain branches, but at the expenses of running time.

The graph traversal returns a timeline that lists the time of each technosphere exchange in the temporalized foreground system. Exchanges that flow from same producer to the same consumer within a certain time-window (default is 'year') are grouped together to reduce the calculation time and complexity of the model.

2.2.2.3 Time mapping

Based on the timing of the processes in the timeline, *bw_timex* matches automatically the processes at the intersection between foreground and background to the processes from the best available background databases. The new best-fitting background producer(s) are uniquely mapped on the same name, reference product and location as the old background producer.

2.2.2.4 Inventory calculation

bw_timex currently contains two approaches to calculate the time-explicit life cycle inventory (LCI): 1) by expanding the original technosphere and biosphere LCA matrices to include the temporal information of the supply chain and the new suppliers using the brightway function "datapackages" and 2) by calculating the dynamic LCI scores of each temporal supplier directly during the graph traversal. Both approaches yield the same result: a timeline of the biosphere flows stemming from the time-resolved inventories. Approach 1 has the advantage of retaining the matrix-based calculation schema, allowing further investigations and analysis requiring specifically a matrix-based representation of the system under study. Approach 2 has shorter runtimes and is suited typically suited for those users not requiring further elaboration the results and/or studying big systems requiring long runtime. The user can choose which of the two approaches is suitable to their needs.

2.2.2.5 Static impact assessment

Static life cycle impact assessment (LCIA), the default approach in LCA, assigns one characterization factor per substance, regardless of when the emission of the substance occurs. For comparability and transparency, the original static life cycle inventories are also reported in bw_timex. These are the biosphere flows that stem from the original supply chain, without any temporal modifications. Static LCIA can be applied to these original inventories as well as to the time-explicit inventories, for which the biosphere flows correspond to those reported at the specific timing of the process. This gives static results i.e. one figure with the cumulative impact over a specified time horizon, e.g. 100 years, ignoring when exactly the emissions occur. Applying static LCIA methods on time-explicit inventories allows the users to also know when the impacts occur over time. The cumulative results of a dynamic LCI characterized with static LCIA are, at the net of the approximation due to the graph traversal algorithm, the same of the static calculation[8]. The comparison of these two analyses can also help spotting eventual issues in the LCI. Using static LCIA, however, does not allow to consider the changes in impacts induced by the timing of the emissions, which can be covered with the use of a dynamic LCIA method (see section 2.2.2.6 Dynamic impact assessment).

2.2.2.6 Dynamic impact assessment

As *bw_timex* includes the timing of the emissions from the time-resolved supply chain, dynamic impact assessment methods can be applied. dynamic impact assessment methods are methods that contain multiple characterization factors for a substance, based on the timing of the emission of the substance. *bw_timex* is built to allow for the use of any dynamic impact assessment method, but currently only metric for 'radiative forcing' and 'global warming potential' (GWP) are provided. The user can choose to provide their own dynamic impact assessment methods or use the already implemented methods. These dynamic methods, hosted in a separate library *dynamic_characterization*[9] take the actual timing of the emission into account and allow the user to choose a flexible time horizon, over which the metric is evaluated. The underlying atmospheric decay and radiative efficiency is based on the IPCC AR6 report (Forster et al. 2021).

2.2.2.7 Interpretation

Lastly, multiple simple functions to plot both the dynamic inventory[10] and the dynamic LCA results are provided, as well as the possibility to show the results as a waterfall (see Figure 5 for example).

[9] https://github.com/brightway-lca/dynamic_characterization
[10] See following section of the notebook as example: https://docs.brightway.dev/projects/bw-timex/en/latest/content/examples/example_ev.html#gwp

While the core functionalities of *bw_timex* are well developed, there might be some future changes. The latest information on functionalities and changes can be found in the online documentation.

2.2.3 Demonstration

This time-explicit method, which can be applied to any type of product and time scale, is being used in the ForestPaths project to assess the substitution potential of forest-based material and energy products in the ongoing task 4.3. In this section a simplified demonstration of the application of bw_timex in the context of wood-based products is shown. Wood-based products are a highly relevant use case for time-explicit LCA because the life cycle of wood-based products can be long, resulting in potentially significant changes in the supply chain in different parts of the life cycle. Moreover, the displacement potential of wood products is calculated by comparing the impact of a wood-based materials with the avoided impact from a fossil-based alternative. Both production systems, including the fossil-based one, will undergo future changes, which might influence the actual saving potential. In addition, the uptake and release of biogenic carbon in the wood are spread over time, adding another temporal layer that is relevant to capture and properly in LCA.

In the example, the substitution benefits replacing a fossil-based industrial hall (steel and concrete-based) with a wood-based one is assessed from a gate-to-grave (i.e. from forest-road to its end-of-life) perspective using a prospective and dynamic LCA method (**Error! Reference source not found.**Table 1). For this example the substitution is calculated as reduction in Global warming impact per kg of carbon contained in the wood product (CO_2eq/kg C in wood).

Table 1: Data and assumptions of the case study.

Variable	Wood product	Fossil alternatives
Product	Industrial hall	Steel hall (50%) Reinforced concrete hall (50%)
Functional unit	1 kg of wood in product	functionally equivalent amount
Lifetime	50 years	50 years
System boundary	Gate-to-grave	Gate-to-grave
Data source	FORMIT Project (Valada et al. 2016)	FORMIT Project (Valada et al. 2016)
Background scenario in premise	SSP2-RCP19	SSP2-RCP19
LCIA method	GWP100 (IPCC 2013)	GWP100 (IPCC 2013)
Temporal Distributions	Production spread across 4 years: 2020 to 2024, End-of-Life: 2074	Production in one year: 2024, End-of-Life: 2074

The first step of the analysis consists in generating the time-based background databases with the tool *premise* (Sacchi et al., 2022). The selected scenario (SSP2-RCP19) corresponds to a 1.5C target and the background databases are generated for the years 2020 and 2050[11].

Next, the foreground system of the functionally equivalent wood product and its fossil alternative are modelled after Valada et al., 2016. They assume that a wood-based industrial hall replaces a steel-based and reinforced concrete-based industrial hall at equal shares (50%). The use phase is excluded from the modelling since, being the product compared functionally equivalent, it is assumed that the emission in this stage is the same for both alternatives. The production phase of the wood product is assumed to occur across 4 years[12], while the production of the fossil-based product is modelled within one 2024.

With the provided time-explicit foreground LCIs and time-based background databases, *bw_timex* traverses the supply chain of the product generating, as intermediate result, a timeline of the processes in the system (see Table 2).

Table 2: Timeline of the case study in *bw_timex*. The column "interpolation_weights" shows how to map the respective process to the available databases based on its timestamp.

date_producer	producer_name	date_consumer	consumer_name	amount	interpolation_weights
01/01/2020	market for sawlog and veneer log, softwood, me...	01/01/2022	_Sawnwood, softwood, raw {Europe without Switz...	1.461107	{'db_2020': 1}
01/01/2021	steel production, converter, low-alloyed	01/01/2021	_Steel market production mix RER/U	0.63	{'db_2020': 0.8998083766767041, 'db_2030': 0.1...
01/01/2021	steel production, electric, low-alloyed	01/01/2021	_Steel market production mix RER/U	0.37	{'db_2020': 0.8998083766767041, 'db_2030': 0.1...
01/01/2021	_Steel market production mix RER/U	01/01/2024	_softwood, primary construction, glulam beam, ...	16.5	None
01/01/2022	_Electricity	01/01/2022	_Sawnwood, board, softwood, raw, dried (u=20%)...	13.3	None
...	...	...	...	...	...
01/01/2074	treatment of waste concrete, inert material la...	01/01/2074	_Concrete waste average	0.15	{'db_2050': 1}
01/01/2074	treatment of waste wood, untreated, municipal ...	01/01/2074	_Disposal, wood, 20% water on dry mass basis, ...	1	{'db_2050': 1}
01/01/2074	treatment of wood ash mixture, pure, landfarming	01/01/2074	_CITEPA wood combustion emissions, 20% water o...	0.000119	{'db_2050': 1}

[11] To simplify the comprehension of the demonstration only the initial and final years and not all the time steps of the time horizon studied have been used, as will be done in task 4.3.
[12] Assumption relatively realistic but made to show potentiality of the software.

01/01/2074	heat production, at hard coal industrial furna...	01/01/2074	_Avoided impact after incineration, wood, 20% ...	0.3024	{'db_2050': 1}
01/01/2074	heat production, at hard coal industrial furna...	01/01/2074	_Avoided impact, energy recovery in boiler	0.690589	{'db_2050': 1}

In the next step, *bw_timex* retrieves the temporal explicit inventories in this timeline and characterizes them either with static or with dynamic LCIA methods. To simplify the comprehension of this demonstration, only the results for the static LCIA methods are shown and discussed (Figure 5). The online tutorials provide additional results for the dynamic LCIA functions.[13]

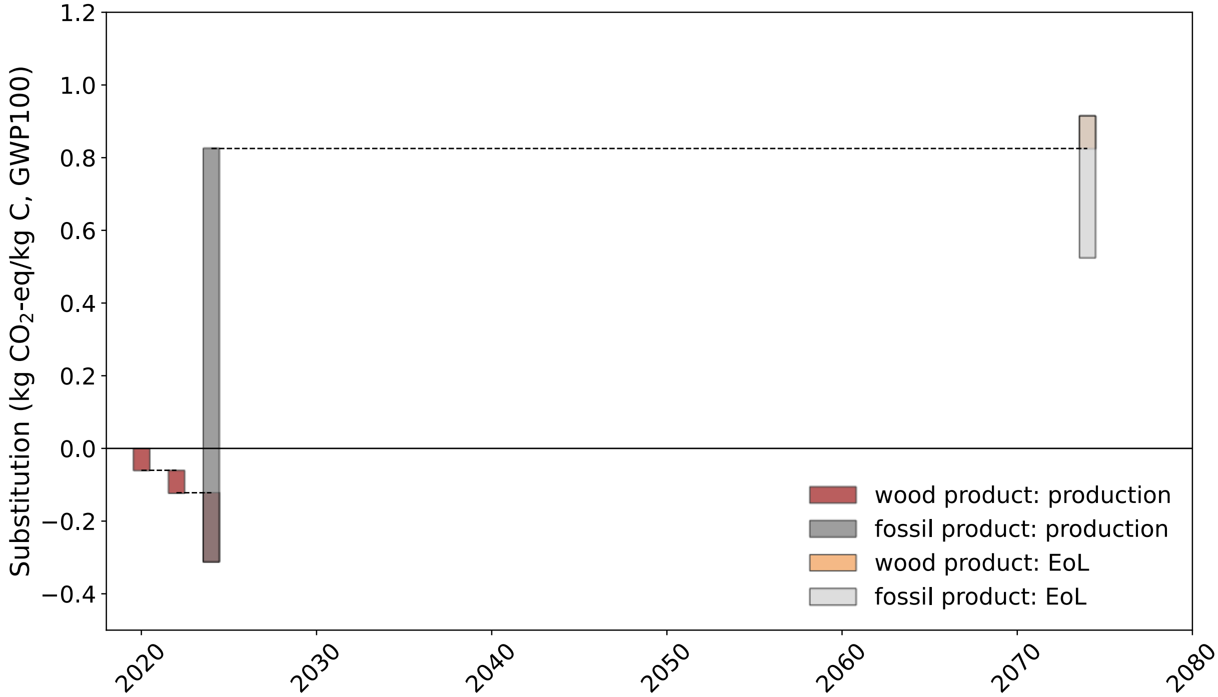

Figure 5: Waterfall chart showing the impacts (positive) and savings (negative) of the wood vs the fossil product per supply chain stage (production and EoL) over time. Positive values correspond to a saving, negative to a emission of kg CO2-eq per kg of carbon contained in the wood product when using wood instead of the fossil alternative.

Between 2020 and 2024, a negative impact is caused by the emissions occurring during the production of the wood-based industrial hall (red bar). In 2024, the impacts due to the production of the fossil-based industrial hall are avoided, resulting in a benefit (green bar). In 2074, the end-of-life of the wood product, which assumes incineration with energy recovery, increases the substitution benefit. On the contrary, at the end of its life the steel in the fossil-based products is assumed to be recycled. This contributes to reduce its total impact and, consequently, also the overall substitution benefits which is, in total, 0.53 kg CO2-eq per kg of carbon contained in the wooden industrial hall.

[13] https://docs.brightway.dev/projects/bw-timex/en/latest/content/examples/example_simple_dynamic_characterization.html

s

3 aiphoria

3.1 Background

Material Flow Analysis (MFA) is referred to as a "systematic assessment of the state and change of materials flow and stock in space and time" and is built on the mass conservation principle (Brunner and Rechberger 2004, 2016). MFA tracks the flow of materials in a well-defined system and can be used to represent and reinforce scientific support for decisions concerning the environmental management of natural resources (Lombardi et al. 2023). In the wood sector, MFA is used to depict the flow of wood in the different sub-sectors of the supply chain (Cazzaniga, N., Jasinevičius, G. and Mubareka, S. 2022), asses the level of circularity of the sector, (Gonçalves et al. 2021) and determine the amount of wood, and consequently carbon, stocked in the in-use products (Jasinevičius et al., 2015).).

A few models exist for carbon accounting of wood products (Brunet-Navarro et al. 2016; Jasinevičius et al. 2015) but, at least to the author's knowledge, the are no open source software that allow to represent wood flows and calculate their carbon impact in terms of stock and flow. While there are few tools to conduct MFA, none of is openly and readily available and can accommodate dynamic, other than static, MFA (Lindner et al. 2010; Jasinevičius 2018; Jasinevičius et al. 2018).

To address this gap and achieve the project goal of conducting a dynamic wood material flow analysis and a carbon storage assessment for the EU forest sector at an unprecedented resolution, we have developed *aiphoria*, an open-source software library specifically designed for wood flow analysis. Aiphoria can be used to couple temporally dynamic *aiphoria*, is built on top of ODYM (Open Dynamic Material Systems Model) (Pauliuk and Heeren 2020), and facilitates the assessment of wood materials flows, their visualization as well as their translation in carbon stocks and stock changes over time. ODYM is a powerful, developed, and maintained tool for studying material systems dynamically. It allows for the tracking of multiple elements (e.g., it combines both wood flow and carbon stock analysis) while also studying different decay functions. *aiphoria* incorporates all the aspects of ODYM while also being tailored to the particularities of the wood sector (Orfanidou et al., 2024).

3.2 Software

aiphoria is an open-source software designed to facilitate the assessment and visualization of wood materials flows over time. Built on top of ODYM library (Pauliuk and Heeren 2020), *aiphoria* leverages ODYM's flexible and versatile framework for modeling biophysical stock-flow relations in socioeconomic metabolism. While ODYM is highly adaptable for various specific applications and sectoral contexts, it requires significant effort and detailed knowledge to build an MFA model. Its openness and versatility were exploited to build *aiphoria*, that reduces the complexity of ODYM and simplifies the development and analysis of wood flow models. *aiphoria* is released as open-source and its source code is hosted on GitHub[14] and supports both inflow-driven, and stock-

[14] https://github.com/EuropeanForestInstitute/aiphoria

driven MFA models. *aiphoria* is licensed under the MIT License, allowing free use, modification, and distribution, provided that the original copyright notice and permission notice are included in all copies.

Key Features of *aiphoria*

1) System definition and Data Management

- Users can specify the model within a single, user-friendly input file.
- *aiphoria* is fully flexible for what concerns supply chain representation and allows users to define the MFA system (processes or product as nodes and flows between them) at any resolution. For instance, users are free to decide if to represent the system with a set of process, products, or a combination of them, their number, and to decide how to cluster them into transformation stages.
- *aiphoria* allows users to define the MFA system using both absolute and relative (%) values (see Table 4). For instance, users can input statistics for semi-finished wood product in absolute values (e.g. m^3 or tonnes of wood product *a* used in year *t*) and calculate how much is used in the various end-uses for which allocation in relative terms (%) are known (e.g. x% of *a* is used in product b and y% in product c in year *t*).
- The tool ensures data integrity by checking and validating input data as well as by checking mass balances. Specifically, *aiphoria*, checks that all the mandatory parameters are provided and if they are in the correct form in the input file and provides feedback / error messages to the user.
-

2) Dynamic MFA and temporary carbon accounting

- The software supports dynamic MFA, allowing users to conduct analyses that consider changes over time, and carbon accounting to track stocks and flows of carbon in the system under study.

3) Visualization capabilities

- *aiphoria* provides visualization tools, including the creation of dynamic Sankey diagrams, offering a clear and dynamic representation of material circulation within the system.
- The software generates plots for yearly stocks of both wood and carbon as well as metrics such as in-use stocks, stock changes, stock outflows, and annual CO_2 emissions and removals (see footnote 17).

3.2.1 Method

The specific steps which describe *aiphoria* can be seen in Figure 6.

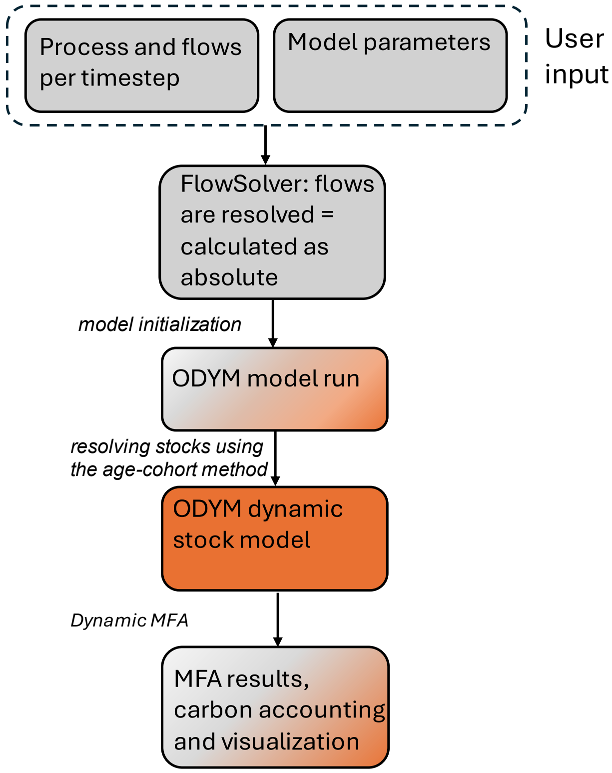

Figure 6: aiphoria procedure and its integration to ODYM. Grey color indicates *aiphoria* core code, while orange the parts that ODYM is utilized.

3.2.1.1 User input

As a first step, the user defines the system which entails specifying the processes/products (Table *3*) and flows (Table 4) of the system under study. This can be done using the input file available in GitHub[15].

The file requires the user to define all mandatory parameters, but it can also accommodate any number of, user-defined, optional ones. These optional fields can e.g. be used to help interpreting the results or perform further analysis (e.g., conversion between different Unit field in the Flows tab). For example, all the optional fields in Table *3* and Table 4 have been added to facilitate the analysis for the project and the work of deliverable 4.1.

aiphoria is not bound to a specific unit, but is the user that has to define the base unit in the Value field of the Flows tab. The base unit is the unit to be used in the MFA (e.g. m3 SWE in the example below). Any conversion made (e.g. to carbon) will be made from the base unit to the desired one using appropriate conversion factor.

[15] Input file: https://github.com/EuropeanForestInstitute/aiphoria/tree/main/template

Table 3: Description of the fields of the input file to define Products/processes. *aiphoria* can accept any number and type of optional field in addition to those already defined in the tool. Those optional field shown in this table marked with a star have been added for the project for documentation / bookkeeping purposes.

Field name	Description	Data type	Optional (O) or Mandatory (M)
Process/product	Process/product names (e.g., Sawnmill/Sawnwood).	String	M
Process/product location	Geographical location of the process/product (e.g., EU).	String	M
Process/product ID	Creation of process/product ID based on the process/product name and process/product location (e.g., Sawnwood:EU).	String	M
Transformation Stage	Transformation stage within the supply chain (e.g., Source or First).	String	M
Lifetime	Lifetime of stocks (e.g., 10 years). For processes without lifetime, 0 can be applied meaning that the inflow is becoming outflow at the same year.	Integer	M
Distribution type	Type of probability (i.e., *Fixed, Normal, LogNormal, FoldedNormal, or Weibull*)) distribution which passes to ODYM and is applied to stocks for its outflows (=stock decay). More information on the types refer to ODYM documentation.	String	M
Distribution parameters	*StdDev* applied in case of *Normal* distribution, *LogNormal* or *FoldedNormal* (e.g., 0.4 for standard deviation of lifetime). For *Weibull* distribution *shape* and *scale* parameters need to pass in ODYM (e.g., shape=1.5, scale=5). If *Fixed* distribution is chosen, the distribution parameters inputs are ignored.	Tuple (for stddev) or list of parameters separated by comma (for shape and scale)	M
Comment	Any comment regarding the process.	String	O
Normalized X	X position of process/product in the Sankey diagram. If not defined from the user automatically set from *aiphoria*	Float	O
Normalized Y	Y position of process/product in the Sankey diagram. If not defined from the user automatically set from *aiphoria*	Float	O
Label shown in the graph	Label shown for the process/product in the Sankey diagram	String	O

Wood Content (%)*	m^3 SWE in the process/product.	Tuple	O
Wood content source*	Source of the wood content figure.	String	O
Density (kg/m^3)*	Density of process/product.	Float	O
Modelling status*	Information on modelling status	String	O

Table 4 Description of the fields of the input file of aiphoria to define flows. All processes that will be used in the Flows tab should have already been defined in the Process tab. *aiphoria* can accept any number and type of optional field in addition to those already defined in the tool. Those optional field shown in this table marked with a star have been added for the project for documentation / bookkeeping purposes.

Field name	Description	Data type	Optional or Mandatory
Source Process/product	Source Process Name of the flow (e.g., Sawnwood)	String	M
Transformation Stage	Transformation stage of the source process (e.g. First)	String	M
Source Process/product location	Geographical location of the Source Process (e.g., EU).	String	M
Target Process	Target Process Name (e.g., Construction)	String	M
Target Process/product location	Geographical location of the Target Process (e.g., EU).	String	M
Source ID	Creation of flow Source ID based on the source process name and source process location (e.g., Sawnwood:EU)	String	M
Target ID	Creation of flow Target ID based on the target process name and target process location (e.g., Construction:EU)	String	M
Value	Value given to the flow (e.g. 10)	Float	M
Unit	Base unit which can be any unit (e.g., kg, Mm^3, kj)	String	M
Year	The flows are assigned to a specific year (e.g., 2021). To run the model, aiphoria requires at least the given starting year. If the flows are consistent over multiple years (e.g., 2021, 2022, 2023), aiphoria will repeat the inputs from the first year. If different values appear for the same flows	Integer	M

	in different years, all flows should be defined in this tab. The length of the model run is defined in two ways: from the input file using the method described above, and from the model parameters (e.g., year_start:2021 and year_end:2030).		
Data Source*	Data source for Value in the flow.	String	O
Data Source comment*	Comment related to the data source.	String	O
Conversion factor used*	To document if conversion factor from m^3 or tonnes to Mm^3 SWE has been used (e.g., yes / no).	String	O
Carbon content*	Conversion factor from Mm^3 SWE to carbon content used in ForestPaths.	Float	O
Carbon content source*	To add the source or sources used for the carbon content conversion	String	O

To perform a dynamic MFA *aiphoria* provides the possibility to both define the flow between processes for every year explicitly in the input file or, in case these flows are constant over the time horizon studied, to provide them only once in the input file. In this case *aiphoria* will repeat the values entered for the first year for all years that the model is set to run just by indicating start and end year and setting the option "detect_year_range" to False[16].

Another function under the model parameters is the creation of virtual flows (see **Error! Reference source not found.**) in the case of imbalances on the inputs and outputs of processes. This virtual flow can help to spot potential mistakes in the data and ensure that the system studied is mass balanced in the case of inconsistencies in the source data used. Virtual flows do not affect calculations andcan be toggled off by the users.

3.2.1.2 FlowSolver

With the FlowSolver, *aiphoria* resolves the provided flows for each specific timestep, meaning it converts the input relative values into absolute. For input errors, the data checker does the data integrity checks, so in case something is wrong a message, which indicates the error within the Processes or Flows tabs appears.

3.2.1.3 ODYM model run

During this step, *aiphoria* passes of the necessary parameters in the proper format to ODYM to create the MFA system.

3.2.1.4 ODYM dynamic stock model

[16] See example notebook: https://github.com/EuropeanForestInstitute/aiphoria/blob/main/example.ipynb

This step calculated the dynamic stock models that track how stocks change over time based on their inflows and lifetime parameters and each result is stored in a dictionary. The created dynamic stock model shows how stocks of wood and carbon change over time.

3.2.1.5 Dynamic MFA results, carbon accounting and visualization

For each of the built dynamic stock model, different results become available where *x* can be as an example stock of wood (*x=swe*), stock of carbon (*x=carbon)* or any other parameter:

- *stock by cohort (x_stock_by_cohort)* which provides the stock, segmented by their year introduction into the system.
  - For example, wood introduced in the stock in the year *x*, may still be accounted for within the same stock in *y*.
- *total or in-use stock (x_stock_total)* reflects the aggregate stock within the system, offering a snapshot of total material quantities at any given time.

- *Stock change (x_stock_change)* denotes the net changes in stock within the system over time, capturing dynamic shifts in stock levels.

- *total outflow (x_o)* which reports the total outflows from the stock, providing an overarching value that reflects total material loss from the system over time.
  - It provides insights, for example, on the total wood outflow from a stock in year *x*.

- *outflow by cohort (x_oc)* which indicates the outflow of materials for each cohort as they reach the end of their lifespan. This helps in understanding the lifecycle of materials and the timing of their exit from the system.

- *Net Annual CO_2 emissions and removals*[17] *(results_net_co2_emissions_removals)* is calculated by using the stock change results and converting them to CO_2 equivalents.
  - It provides insights on the amount of CO_2 stocked within the products per year.

- *Interactive Sankey diagram* which shows the connection of processes with flows of the defined system where the width of arrows is proportional to the flow quantity.
  - It provides information on the flow direction, quantities, visualization of the system and proportionality per year.

3.2.2 Demonstration

This section will present a step-by-step demonstration on how to use *aiphoria*.

1) Set up

[17] If the result of the stock change is positive, it indicates an increase in carbon stocks, which corresponds to a net removal of CO_2 from the atmosphere. If the result is negative, it indicates a decrease in carbon stocks, corresponding to net CO_2 emissions to the atmosphere.

aiphoria can be downloaded from the following open repository: https://github.com/EuropeanForestInstitute/aiphoria

2) User input

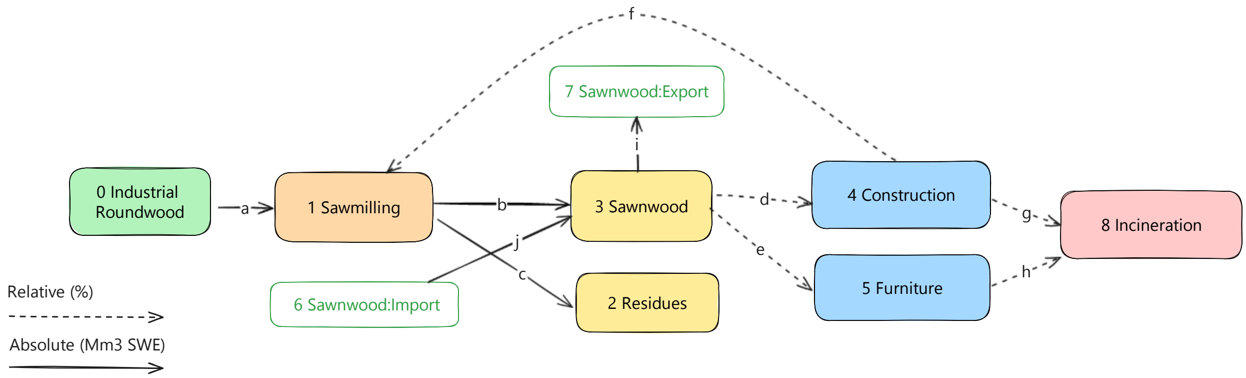

Figure 7: System definition for demo case.

In the example in Figure 7 the demo case is depicted and its *aiphoria*'s input file can be found in the open GitHub repository at the following link together with the Jupyter notebook example.ipynb to reproduce the demo:

https://github.com/EuropeanForestInstitute/aiphoria/blob/main/data/example_data.xlsx
https://github.com/EuropeanForestInstitute/aiphoria/blob/main/example.ipynb

Table 5: Model characteristics for demo case.

	Model characteristics
MFA type	Inflow-driven
Stock lifetimes	Construction (lt: 10 years) and Furniture (lt: 5 years)
Start year (first year of flows)	2021
End year (last year of flows)	2030
Distribution type for stocks	Normal
Standard Deviation (of lifetime)	1

The demo case is an inflow-driven dynamic MFA for a simplified wood supply chain between 2021 to 2030 with flows between processes (i.e. letters in Figure 7) that are constant over the whole-time horizon. There are no initial stocks assumed. In the example, the base unit is Mm^3 SWE and the *Construction* and *Furniture* processes are assumed to have a hypothetical lifetime of 10 and 5 years, respectively.

Figure 8 and Figure 9 shows the *aiphoria* input file for the processes and flows tabs.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1		*string*	*string*	*string*	*string*	*integer*	*string*	*string*	*tuple*	*float*	*string*	*float*	*string*	*string*	*string*	*float*	*float*	*string*
2						*Years*				*%*		*kg/m3*						
3		**Process**	**Process_location**	**Process_ID**	**Transformation_Stage**	**Lifetime**	**Lifetime_source**	**Distribution_type**	**Distribution_parameters**	**Wood_content**	**Wood_content_source**	**Density**	**Density_source**	**Modelling status**	**Comment**	**Normalized X**	**Normalized Y**	**Label shown in graph**
4	0	Industrial_roundwood	FI	Industrial_roundwood:FI	Source	0		Normal	1							0.037	0.347	0 Roundwood
5	1	Sawmilling	FI	Sawmilling:FI	First	0		Normal	1							0.243	0.392	1 Sawmilling
6	2	Residues	FI	Residues:FI	by_prod	0		Normal	1							0.403	0.101	2 By products
7	3	Sawnwood	FI	Sawnwood:FI	Second	0		Normal	1							0.409	0.532	3 Sawnwood
8	4	Construction	FI	Construction:FI	VAM	10		Normal	1							0.752	0.444	4 Construction
9	5	Furniture	FI	Furniture:FI	VAM	5		Normal	1							0.656	0.773	5 Furniture
10	6	Sawnwood	Import	Sawnwood:Import	RoW	0		Normal	1							0.264	0.819	6 Import
11	7	Sawnwood	Export	Sawnwood:Export	RoW	0		Normal	1							0.691	0.165	7 Export
12	8	Incineration	FI	Incineration:FI	EoL	0		Normal	1							0.966	0.483	8 Incineration

Figure 8: Input in the 'Processes' tab of aiphoria for the demo case.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1		*string*	*string*	*string*	*string*	*string*	*string*	*string*	*string*	*float*	*string*	*integer*	*string*	*string*	*string*	*float*	*string*
2											*m3, kg, %*						
3		**Source_process**	**Transformation_Stage**	**Source_process_location**	**Target_process**	**Transformation_Stage**	**Target_process_location**	**Source _ID**	**Target_ID**	**Value**	**Unit**	**Year**	**Data_source**	**Data_source_comment**	**Conversion_factor_used**	**Carbon_content_conversion**	**Carbon_content_source**
4	a	Industrial_roundwood	Source	FI	Sawmilling	First	FI	Industrial_roundwood:FI	Sawmilling:FI	60	Mm3 SWE	2021		Random input values		0.203424	https://doi.org/10.1016/j.resconrec.2024.107476
5	b	Sawmilling	First	FI	Sawnwood	Second	FI	Sawmilling:FI	Sawnwood:FI	50	Mm3 SWE	2021		Random input values		0.203424	https://doi.org/10.1016/j.resconrec.2024.107476, assumed average conversion factor 80% soft 20% hard
6	c	Sawmilling	First	FI	Residues	by_prod	FI	Sawmilling:FI	Residues:FI	19.5	Mm3 SWE	2021		Random input values		0.1896	https://doi.org/10.1016/j.resconrec.2024.107476, assumed average conversion factor 80% soft 20% hard
7	d	Sawnwood	Second	FI	Construction	VAM	FI	Sawnwood:FI	Construction:FI	60	%	2021		Random input values		0.2304	Assumed density of CLT 480 kg/m3
8	e	Sawnwood	Second	FI	Furniture	VAM	FI	Sawnwood:FI	Furniture:FI	40	%	2021		Random input values		0.216	Assumer density of a furniture product 450 kg/m3
9	f	Construction	VAM	FI	Sawmilling	First	FI	Construction:FI	Sawmilling:FI	40	%	2021		Random input values		0.2304	Assumed density of CLT 480 kg/m3
10	g	Construction	VAM	FI	Incineration	EoL	FI	Construction:FI	Incineration:FI	60	%	2021		Random input values		0.216	Assumer density of a furniture product 450 kg/m3
11	h	Furniture	VAM	FI	Incineration	EoL	FI	Furniture:FI	Incineration:FI	100	%	2021		Random input values		0.216	https://doi.org/10.1016/j.resconrec.2024.107476, assumed average conversion factor 80% soft 20% hard
12	i	Sawnwood	Second	FI	Sawnwood	RoW	Export	Sawnwood:FI	Sawnwood:Export	20	Mm3 SWE	2021		Random input values		0.203424	https://doi.org/10.1016/j.resconrec.2024.107476, assumed average conversion factor 80% soft 20% hard
13	j	Sawnwood	RoW	Import	Sawnwood	RoW	FI	Sawnwood:Import	Sawnwood:FI	10	Mm3 SWE	2021		Random input values		0.203424	https://doi.org/10.1016/j.resconrec.2024.107476, assumed average conversion factor 80% soft 20% hard

Figure 9: Input in the 'Flows' tab of aiphoria for the demo case.

3) Model run and dynamic stock model creation

Once *aiphoria* runs successfully, the FlowSolver translates the relative flows to absolute and the carbon content calculation takes place (see Table 6).

Table 6 Flow data in the base unit (Mm^3 SWE) and Tonnes of carbon. As inputs remain the same for the duration of the model aiphoria will use the 2021 flow values.

Year	Source Process ID	Target Process ID	Value (Mm3 SWE)	Value (Million Tonnes of carbon)
2021	Industrial_roundwood	Sawmilling	60	12.20544
2021	Sawmilling	Sawnwood	50	10.1712
2021	Sawmilling	Residues	19.5	3.6972
2021	Sawnwood	Construction	24	5.5296
2021	Sawnwood	Furniture	16	3.456
2021	Construction	Sawmilling	9.6	2.21184
2021	Construction	Incineration	14.4	3.1104

2021	Furniture	Incineration	16	3.456
2021	Sawnwood	Sawnwood:Export	20	4.06848
2021	Sawnwood:Import	Sawnwood	10	2.03424

4) Dynamic MFA results, carbon accounting and visualization

In the next step, the dynamic stock models for *Construction* and *Furniture* are calculated and they information can be visualized as graphs (see Figure 10 and Figure 11 and Annex for quantitative results) and as an interactive and dynamic (i.e. per timestep) Sankey diagram (Figure 12).

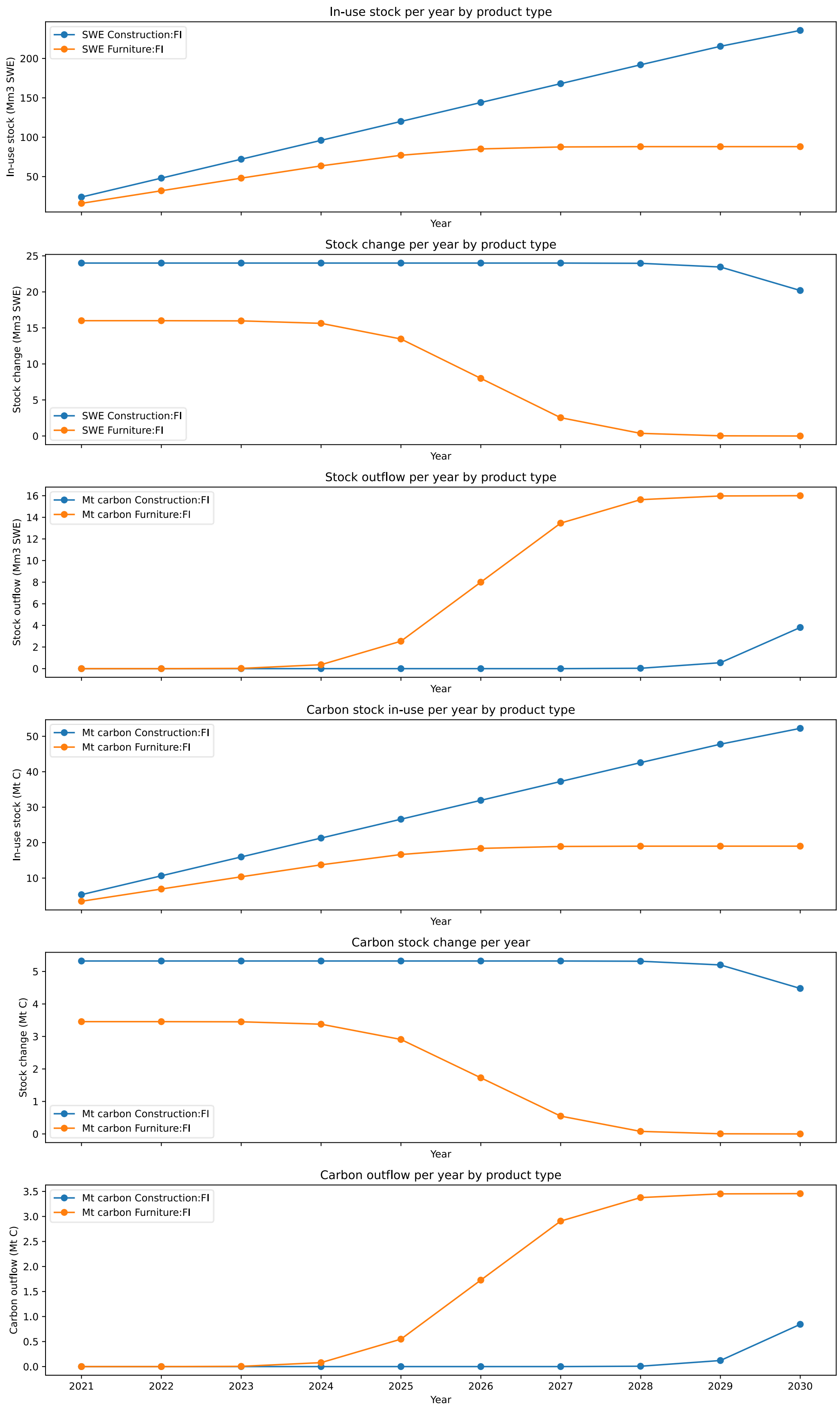

Figure 10: MFA and carbon content demo case results (in-use, stock change, outflow) in Mm^3 SWE and tonnes of carbon per year.

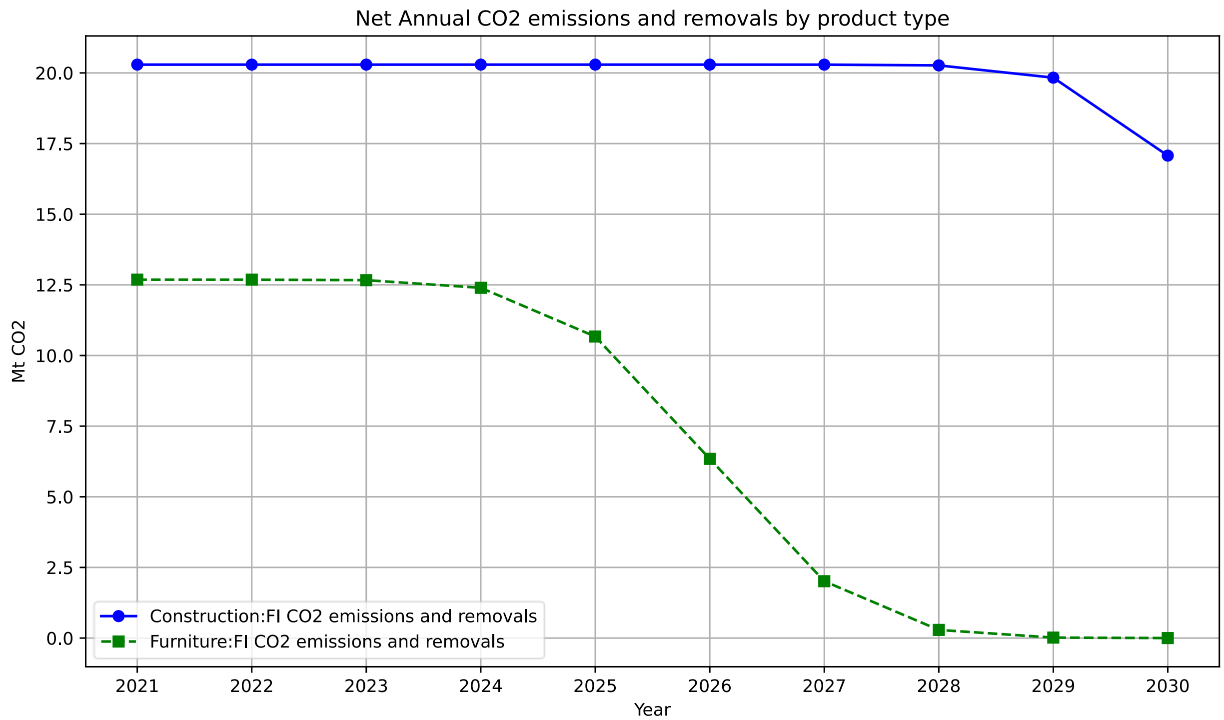

Figure 11: Net Annual CO_2 emissions and removals by product per year for demo case.

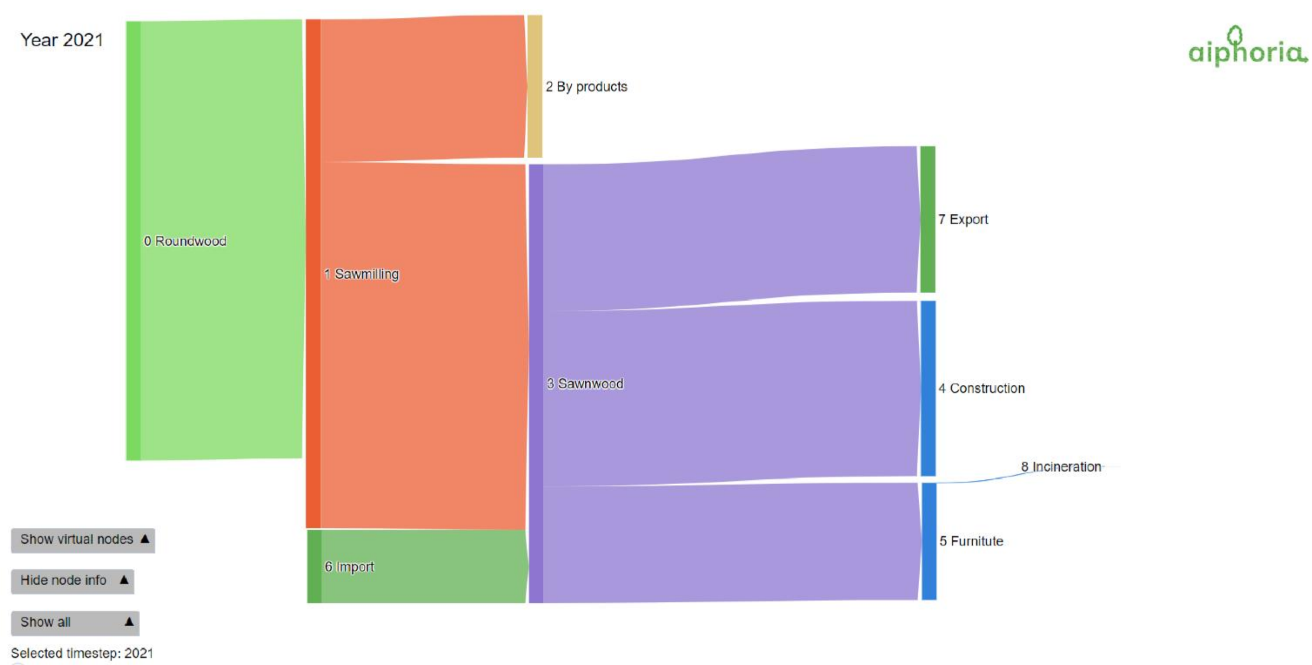

Figure 12: aiphoria interactive Sankey diagram for demo case for year 2021. The demo case is set to run between 2021-2030, in y axis the Sankey diagram for each year can be seen.

4 Discussion and final remarks

In the report, we presented the two open-source software library *bw_timex*, for time-explicit LCA and *aiphoria*, for modelling dynamic wood material flows and temporary carbon storage in wood products. The two tools provide an advanced modelling platform to account for the contribution of wood products to carbon sequestration and their role in climate change mitigation.
While both tools have been demonstrated successfully for a selection of exemplary case studies, there are some limitations and bottlenecks that can be addressed in future work:

bw_timex:

- The calculation time of a timexLCA, if it has a complex supply chain combined with fine temporal distributions and a low cut-off limit, are in the range of minutes and need to be further reduced by investigating and eliminating bottlenecks and redundancies in the code.
- Although several of the functionalities have been unit tested[18], more thorough tests are needed to ensure that the functionalities remain stable and unintended consequences of code changes are avoided.
- Time-explicit relinking of the supply chains is currently only possible for processes in the foreground supply chain. Conceptually, any process in the supply chain, also if it belongs to the background database, should be temporalized. This is currently only possible by moving this segment of the supply chain to the foreground system. Future work should enable a database-agnostic time-explicit relinking algorithm.

aiphoria:

- Although *aiphoria* has been internally tested to minimize the risk of unwanted behavior, no formal unit test has been developed.

4.1 Next steps

The next development steps for the two software packages are listed below.

Bw_timex:

- Extend unit test coverage and integrate/extend the documentation also with other jupyter notebook examples.
- Profile and optimize the software to reduce runtime of big/complex analysis.
- Identify and apply the best approach and tool (e.g. Modular LCA vs superstructure) to be used to model the effect of alternative technological options of wood production needed to create the dynamic, prospective, and combinatorial LCA platform.

aiphoria:

- Package and deploy aiphoria via standard python channels (pypi/anaconda)
- Develop unit testing to properly test *aiphoria*'s components.

[18] https://github.com/brightway-lca/bw_timex/tree/main/tests

- Further improve and add new visualization to support system boundaries definition and dynamic MFA e.g. by allowing for the visualization in the Sankey diagram not only for visualizing the wood flow in the defined base unit but also other unit after conversion (e.g. if Mm^3 SWE as base unit also in carbon). Additionally, if resources allow, an automatic network graph showing process/node connections and flows may be added to help *aiphoria* users quickly understand and optimize the system[19].
- Add additional demo cases and training material to the repository to illustrate all the functionalities and facilitate the use of *aiphoria*.

Other than continuing and improving the two models presented in this deliverable, in the year to come WP4 will continue to work on the creation of the substitution and biodiversity factors as well as the MFA. More specifically the Life Cycle Inventory of the wood and competing products targeted in the project will be integrated with those few products for which data have not been collected yet and their perspective and dynamic modeling further developed e.g. parts of the LCIs needs to be reworked to better reflect a prospective structure (processes need to be replaced with markets) and the combinatorial aspect will be added. Concerning the MFA, the goal for the months to come it so extend the work done for 2021 to the past and future years using respectively the market data from FAOSTAT and the EFI-GTM model.

5 Acknowledgements

bw_timex has been built in collaboration with Timo Diepers from RWTH Aachen and Arthur Jakobs from Paul Scherrer Institute. Chris Mutel, the core developer of *brightway*, has given valuable guidance on *brightway* and *bw_temporalis* and Bernhard Steubing and Jeroen Guinée from the University of Leiden haven given great input concerning LCA theory and methods.

[19] Similar to Figure 7 System definition for demo case.

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Annex

Inputs to dynamic stock modelling in aiphoria

1. **Demo case MFA resolved flows and carbon content (same for 2021-2030 as the inflow remains constant)**

Year	Flow ID	Target Process ID	Source Process ID	Value (Mm3 SWE)	Value (Million Tonnes of carbon)
2021	Industrial_roundwood:FI Sawmilling:FI	Industrial_roundwood:FI	Sawmilling:FI	60	12.20544
2021	Sawmilling:FI Sawnwood:FI	Sawmilling:FI	Sawnwood:FI	50	10.1712
2021	Sawmilling:FI Residues:FI	Sawmilling:FI	Residues:FI	19.5	3.6972
2021	Sawnwood:FI Construction:FI	Sawnwood:FI	Construction:FI	24	5.5296
2021	Sawnwood:FI Furniture:FI	Sawnwood:FI	Furniture:FI	16	3.456
2021	Construction:FI Sawmilling:FI	Construction:FI	Sawmilling:FI	9.6	2.21184
2021	Construction:FI Incineration:FI	Construction:FI	Incineration:FI	14.4	3.1104
2021	Furniture:FI Incineration:FI	Furniture:FI	Incineration:FI	16	3.456
2021	Sawnwood:FI Sawnwood:Export	Sawnwood:FI	Sawnwood:Export	20	4.06848
2021	Sawnwood:Import Sawnwood:FI	Sawnwood:Import	Sawnwood:FI	10	2.03424

2. **Demo case Process inputs and outputs (same for 2021-2030 as the flows remain constant)**

Year	Process ID	Total inputs	Total outputs
2021	Industrial_roundwood:FI	0	60
2021	Sawmilling:FI	69.6	69.5
2021	Residues:FI	19.5	0
2021	Sawnwood:FI	60	60
2021	Construction:FI	24	24
2021	Furniture:FI	16	16
2021	Sawnwood:Import	0	10
2021	Sawnwood:Export	20	0
2021	Incineration:FI	30.4	0

Demo case MFA results for Furniture

3. Outflow by cohort for Mm^3 SWE for Furniture stock

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2021	0.00000459	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2022	0.00050215	0.00000459	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2023	0.02109163	0.00050215	0.00000459	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2024	0.34240374	0.02109163	0.00050215	0.00000459	0.0	0.0	0.0	0.0	0.0	0.0
2025	2.17448195	0.34240374	0.02109163	0.00050215	0.00000459	0.0	0.0	0.0	0.0	0.0
2026	5.46151594	2.17448195	0.34240374	0.02109163	0.00050215	0.00000459	0.0	0.0	0.0	0.0
2027	5.46151594	5.46151594	2.17448195	0.34240374	0.02109163	0.00050215	0.00000459	0.0	0.0	0.0
2028	2.17448195	5.46151594	5.46151594	2.17448195	0.34240374	0.02109163	0.00050215	0.00000459	0.0	0.0
2029	0.34240374	2.17448195	5.46151594	5.46151594	2.17448195	0.34240374	0.02109163	0.00050215	0.00000459	0.0
2030	0.02109163	0.34240374	2.17448195	5.46151594	5.46151594	2.17448195	0.34240374	0.02109163	0.00050215	0.00000459

4. Stock by cohort for Mm^3 SWE for Furniture

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2021	15.99999541	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2022	15.99949326	15.99999541	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2023	15.97840163	15.99949326	15.99999541	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2024	15.63599789	15.97840163	15.99949326	15.99999541	0.0	0.0	0.0	0.0	0.0	0.0
2025	13.46151594	15.63599789	15.97840163	15.99949326	15.99999541	0.0	0.0	0.0	0.0	0.0
2026	8.00000000	13.46151594	15.63599789	15.97840163	15.99949326	15.99999541	0.0	0.0	0.0	0.0

2027	2.53848406	8.00000000	13.46151594	15.63599789	15.97840163	15.99949326	15.99999541	0.0	0.0	0.0
2028	0.36400211	2.53848406	8.00000000	13.46151594	15.63599789	15.97840163	15.99949326	15.99999541	0.0	0.0
2029	0.02159837	0.36400211	2.53848406	8.00000000	13.46151594	15.63599789	15.97840163	15.99949326	15.99999541	0.0
2030	0.00050674	0.02159837	0.36400211	2.53848406	8.00000000	13.46151594	15.63599789	15.97840163	15.99949326	15.99999541

5. Carbon Outflow by Cohort per year for Furniture (Mt of carbon)

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2021	0.00000099	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2022	0.00010847	0.00000099	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2023	0.00455579	0.00010847	0.00000099	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2024	0.07395921	0.00455579	0.00010847	0.00000099	0.0	0.0	0.0	0.0	0.0	0.0
2025	0.46968810	0.07395921	0.00455579	0.00010847	0.00000099	0.0	0.0	0.0	0.0	0.0
2026	1.17968744	0.46968810	0.07395921	0.00455579	0.00010847	0.00000099	0.0	0.0	0.0	0.0
2027	1.17968744	1.17968744	0.46968810	0.07395921	0.00455579	0.00010847	0.00000099	0.0	0.0	0.0
2028	0.46968810	1.17968744	1.17968744	0.46968810	0.07395921	0.00455579	0.00010847	0.00000099	0.0	0.0
2029	0.07395921	0.46968810	1.17968744	1.17968744	0.46968810	0.07395921	0.00455579	0.00010847	0.00000099	0.0
2030	0.00455579	0.07395921	0.46968810	1.17968744	1.17968744	0.46968810	0.07395921	0.00455579	0.00010847	0.00000099

6. Carbon Stock by Cohort per year for Furniture (Mt of carbon)

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2021	3.45599901	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2022	3.45589054	3.45599901	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2023	3.45133475	3.45589054	3.45599901	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2024	3.37737554	3.45133475	3.45589054	3.45599901	0.0	0.0	0.0	0.0	0.0	0.0

2025	2.90768744	3.37737554	3.45133475	3.45589054	3.45599901	0.0	0.0	0.0	0.0	0.0
2026	1.72800000	2.90768744	3.37737554	3.45133475	3.45589054	3.45599901	0.0	0.0	0.0	0.0
2027	0.54831256	1.72800000	2.90768744	3.37737554	3.45133475	3.45589054	3.45599901	0.0	0.0	0.0
2028	0.07862446	0.54831256	1.72800000	2.90768744	3.37737554	3.45133475	3.45589054	3.45599901	0.0	0.0
2029	0.00466525	0.07862446	0.54831256	1.72800000	2.90768744	3.37737554	3.45133475	3.45589054	3.45599901	0.0
2030	0.00010946	0.00466525	0.07862446	0.54831256	1.72800000	2.90768744	3.37737554	3.45133475	3.45589054	3.455999009