AquaSPICE

Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations

# Dynamic Life Cycle Assessment

## The AquaSPICE Approach

Dr Athanasios Angelis-Dimakis, University of Huddersfield

AquaSPICE Summer School 2024

The AquaSPICE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958396.

# Dynamic Life Cycle Assessment

- In general, the term "**dynamic**" is used to express a system which is characterized by constant change.
- The changes that characterize a dynamic system can be:
  - directly linked to the operation of the system itself, affecting its performance in the short term
  - linked to the environment, which will affect the system and its performance indirectly, and probably in the longer term.
- However, usually these changes are not considered when assessing the system's environmental impact through a traditional static LCA.

# LCA in the context of I4.0

- Static LCA, based on data from historical time series, enables the stakeholders to better understand the environmental impacts caused by the product system under consideration.
- At the same time though the digital transformation of the industry is one of the biggest shifts we see moving forward.
- Production processes are in the throes of Industry 4.0 transformation, towards a more agile, resilient, and flexible way of operation which increases their capacity to response rapidly to challenges

# LCA in the context of I4.0

- New tools based on real-time modelling as well as robust data-driven approaches, enable the formation of Cyber-Physical Systems (CPS) and allow to better monitor processes and to operate systems much more efficiently.
- Thus, in the context of Industry 4.0 and the CPSs, static LCA is inflexible, providing only a single static snapshot in the time of the complex interactions of a product system.
- That means, it cannot be used to identify hotspots and trade-offs in real-time and support operational actions. The developed concept of Dynamic LCA could overcome these barriers.

# Dynamic Life Cycle Assessment

- Dynamic Life Cycle Assessment can be defined as the LCA that incorporates elements of temporally induced changes that affect the results and the interpretation of the modeled system
- However:
  - Can we use the same framework for Dynamic LCA?
  - Which part of LCA will be dynamic?
  - Are there any differences regarding indicators/data requirements?

# Life Cycle Assessment ISO14040

- What is the purpose of the study and the reference flow of the analysis?
- What are the boundaries of the system?

**Step 1.** Goal and Scope Definition

- What are the materials involved in the system
- What are the values of the corresponding flows?

**Step 2.** Life Cycle Inventory

- Which flows correspond to each environmental impact?
- What are the main environmental impacts?

**Step 3.** Life Cycle Impact Assessment

**Step 4.** Results Interpretation

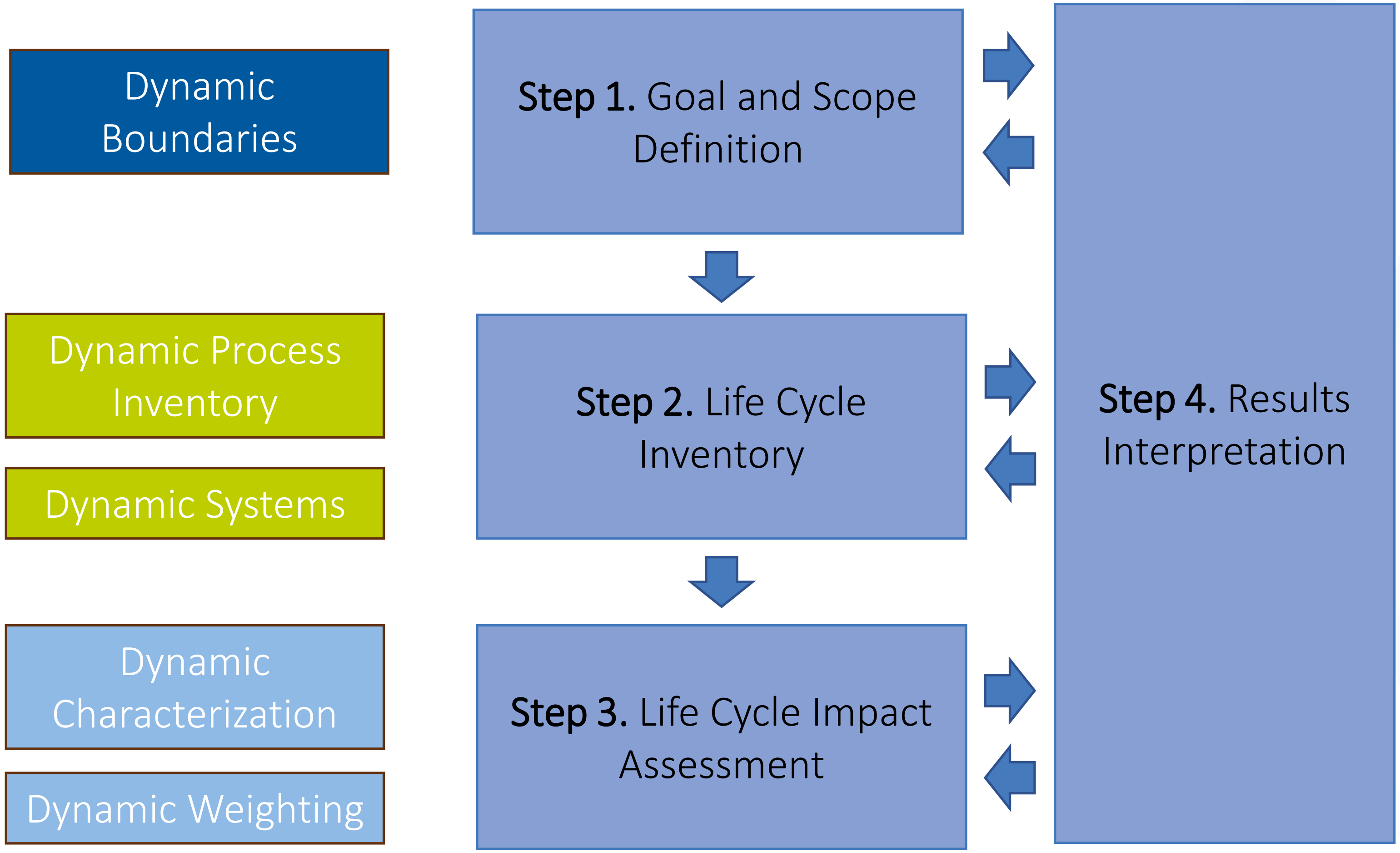
- What do the results indicate?
- What should be the next actions?

# From LCA to Dynamic LCA

A proposed methodological framework

- Sohn et al (2020) suggested an adapted methodological approach where, the first and last steps remain unchanged but the other can be converted into dynamic.
- Three different types of dynamism are described:
  - Dynamic Process Inventory (DPI), which is the most frequently applied type of dynamism, implements temporal changes in input and/or output flows.
  - Dynamic Systems (DSys), where changes are implemented in unit processes within the modelled systems.
  - Dynamic Characterization (DChar), where the characterization factors change temporally.
- DPI and DSys are the dynamic variations of the LCI, whereas DChar is the dynamic implementation of LCIA.

# Life Cycle Assessment ISO14040

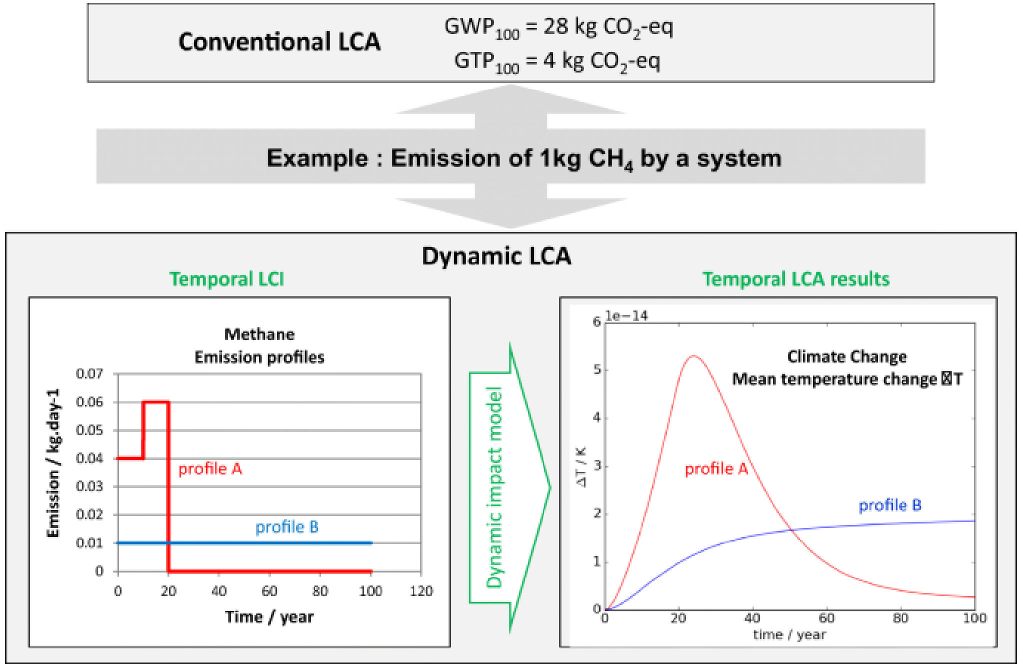


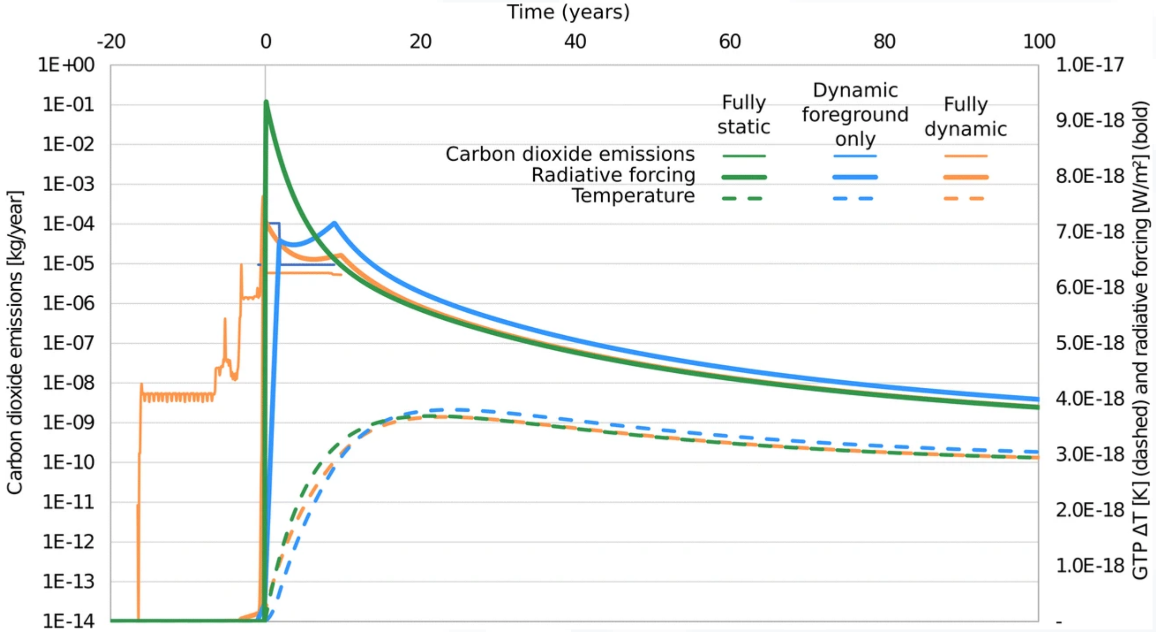
# Dynamic Characterization

- Characterization factors change temporally
- Dynamic characterization based on the expected global temperature changes and time-adjusted cumulative radiative forcing (CRF), as defined by the IPCC to express the global warming potential
- Time-horizon-dependent ecotoxicity characterization factors, developed based on the USEtox fate model
- Time horizon-adjusted CFs for acidification, ozone depletion
- Long term consideration: 100-500 years' time horizon

# Dynamic Characterization

## Examples from Literature




**Source:** Pigné, Y., Gutiérrez, T.N., Gibon, T. *et al.* A tool to operationalize dynamic LCA, including time differentiation on the complete background database. *Int J Life Cycle Assess* **25**, 267–279 (2020). https://doi.org/10.1007/s11367-019-01696-6

# Dynamic Inventory

Long Term Scenarios vs Real Time Monitoring

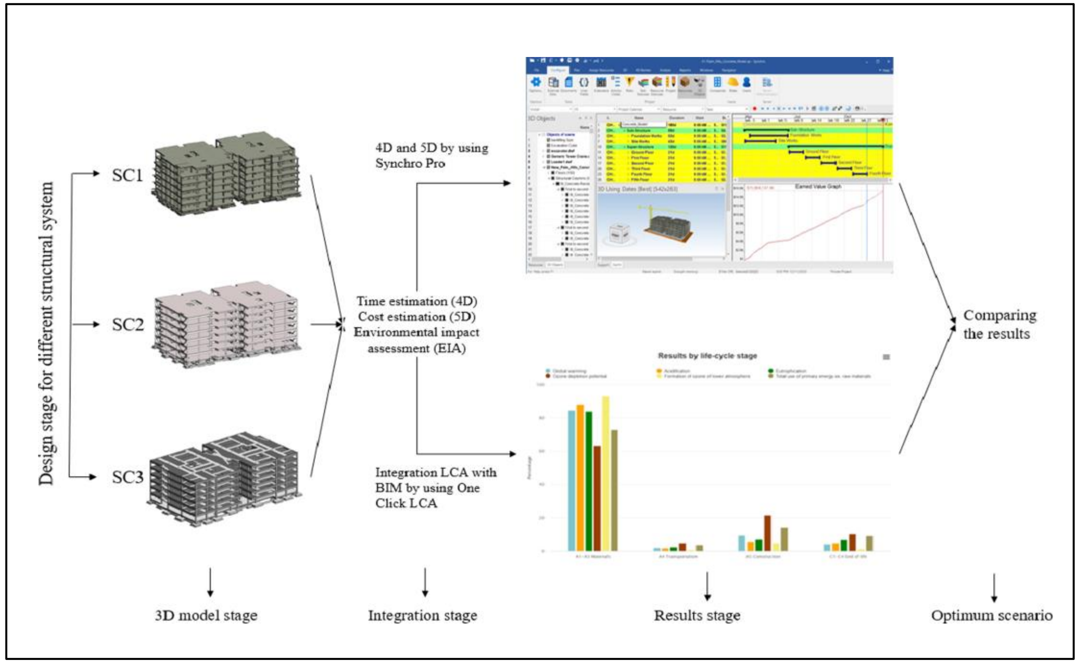
- Using Scenarios
  - The most frequently applied type of dynamism, implementing temporal changes in input and/or output flows
  - Most common application is based on the development of future scenarios
- Real Time
  - In conjunction with real time monitoring systems
  - Real time data collection to continuously update the inventory
  - Why would you need to do that? Which sectors?

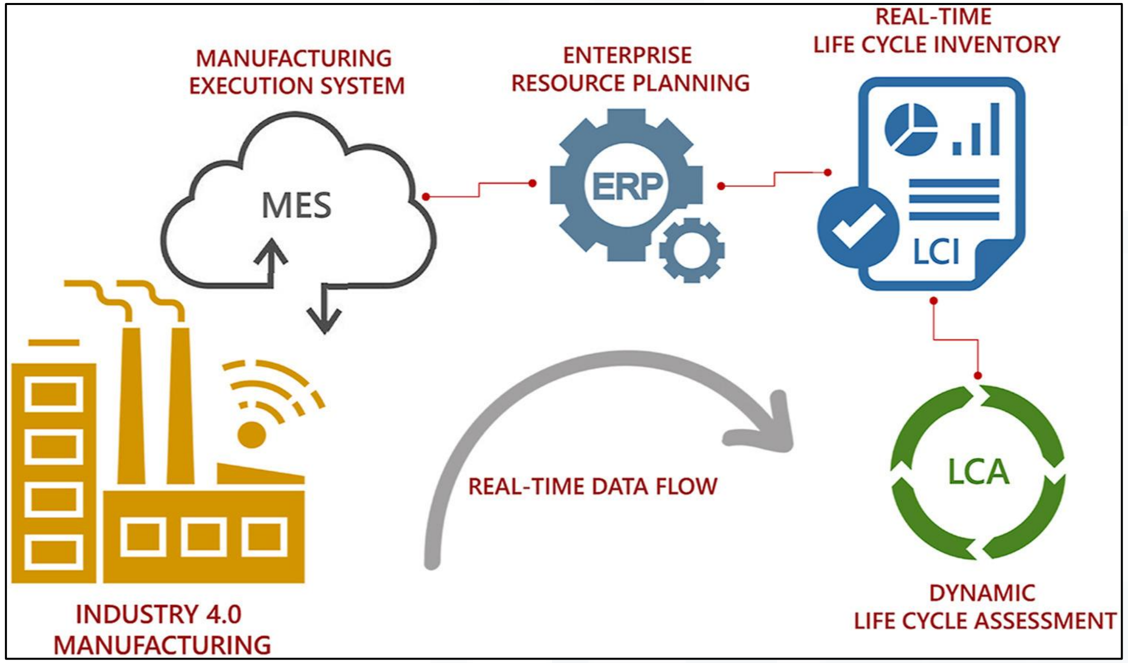
# Dynamic Systems

Examples from Literature

- Dynamic Process Modelling, where changes are implemented in unit processes within the modelled systems
- Used in conjunction with/incorporated into existing process modelling tools
- Common application in the building sector with the Building Information Model (BIM), a tool developed for monitoring the building over its entire life cycle, by collecting an interoperable data set

# Dynamic Systems




**Source**: Morsi D., Ismaeel W., Ehab A., Othman A., BIM-based life cycle assessment for different structural system scenarios of a residential building, *Ain Shams Engineering Journal*, 13(6), (2022) https://doi.org/10.1016/j.asej.2022.101802.

**Source:** Ferrari A.M., Volpi L., Settembre-Blundo D., García-Muiña F. "Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment, *Journal of Cleaner Production*, 286 (2021) https://doi.org/10.1016/j.jclepro.2020.125314

# Dynamic Life Cycle Assessment

The AquaSPICE Approach

- From the four steps of LCA, three have been incorporated in the Dynamic Life Cycle Assessment AquaSPICE framework:
  - Dynamic Goal and Scope (via link to PSM)
  - Dynamic Life Cycle Inventory (via link to RTM and PSM)
  - Dynamic Interpretation (via link to WaterCPS)
- Dynamic Characterisation is not suitable for short-term (near real time) life cycle assessment
  - Characterisation Factors will only change in the long term (50 or 100 years), and definitely not in a very short time horizon

# Let’s try an example…

## Slaughterhouse Wastewater Treatment

- A slaughterhouse in Romania wants to assess the environmental impact of alternative options for their wastewater treatment facilities.
- A volume-based unit is the most common functional unit in the LCA of wastewater treatment and, for this study, 1 $m^3$ of wastewater effluent prior to entering the wastewater treatment system is chosen.
- The focus of the study was the operational Life Cycle Assessment on the water line, which implies that the design, building and maintenance of different process equipment have not been included.

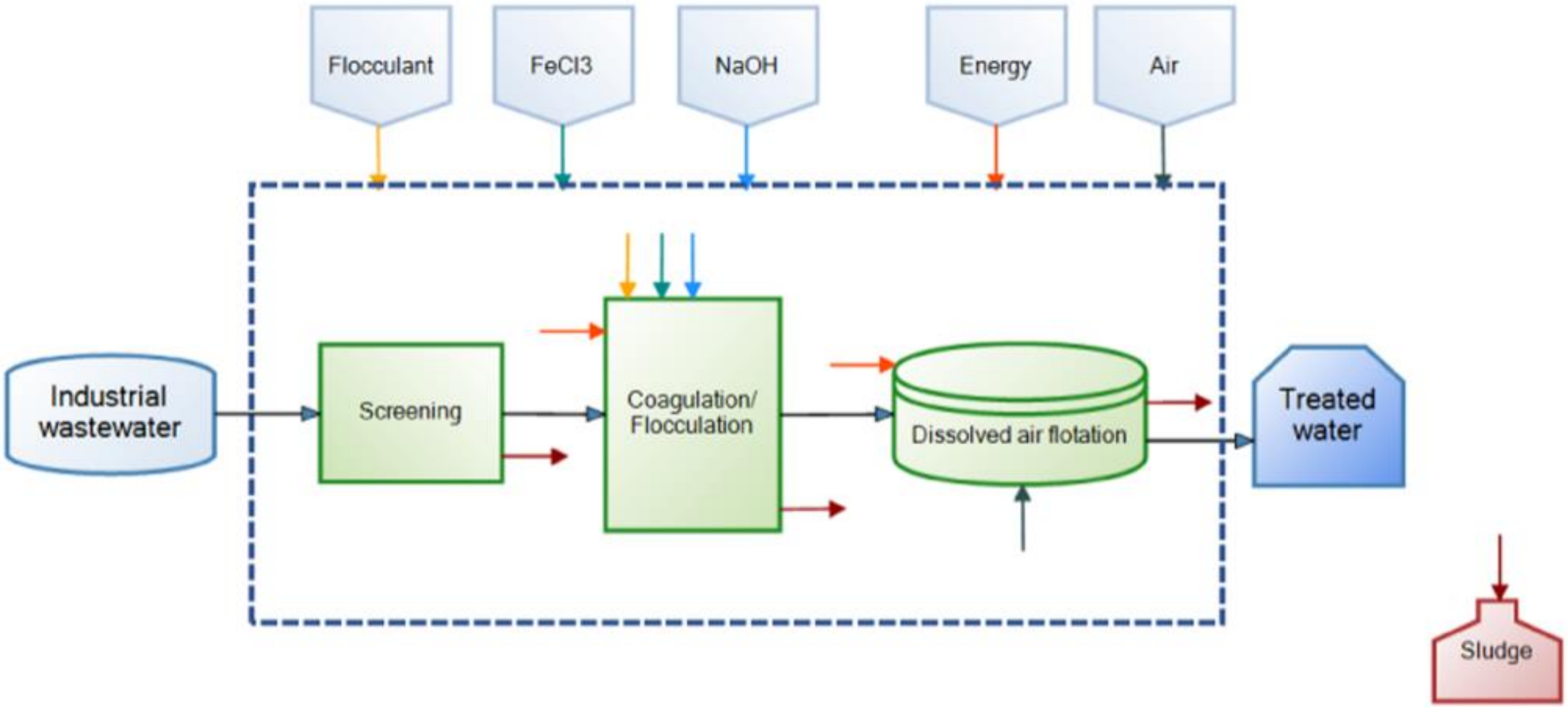
# Life Cycle Assessment

## Main Assumptions

- The Environmental Footprint (EF) impact assessment method has been selected for the impact assessment of the alternative scenarios.
- The EF is an LCA methodology, adopted by the European Commission in the Environmental Footprint transition phase of the commission to incentivise industries manufacturing products with improved environmental performance, based on reliable, verifiable, and comparable information.
- Version 3.7.1 of the ecoinvent database was used for the assessment.

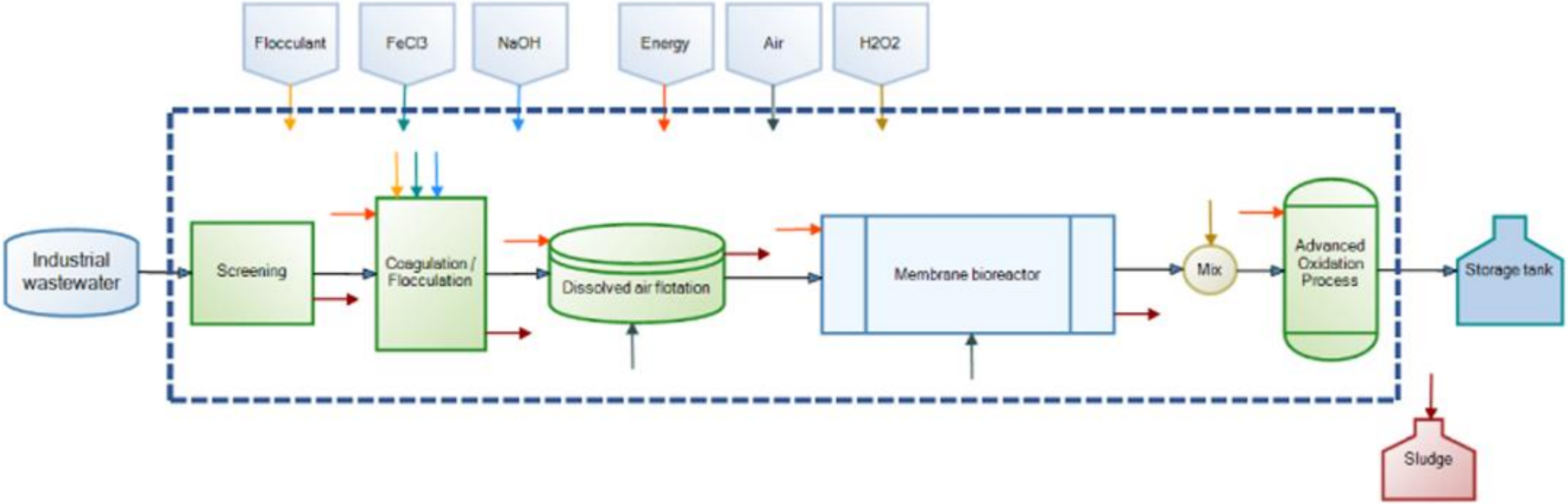
# Option 1 for Wastewater Treatment

As modelled and illustrated using the PSM tool developed by TUC



# Option 2 for Wastewater Treatment

As modelled and illustrated using the PSM tool developed by TUC



# Life Cycle Inventory

## Inputs and Outputs

The Life Cycle Inventory has been populated using: (a) real-time data from online sensors and (b) outputs from a process simulation and modelling tool (digital twin of the process)

Life Cycle Inventory – Input with the functional unit as 1 $m^3$ of wastewater prior to entering the wastewater treatment system.

| Resource | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Ferric (III) Chloride | - | 462 $g/m^3$ | 462 $g/m^3$ |
| Sodium Hydroxide | - | 270 $g/m^3$ | 277 $g/m^3$ |
| Flocculant | - | 5.05 $g/m^3$ | 5.05 $g/m^3$ |
| Hydrogen peroxide | - | - | 50.0 $g/m^3$ |
| Electricity (for coagulation) | - | 0.276 $kWh/m^3$ | 0.276 $kWh/m^3$ |
| Electricity (for DAF) | - | 0.170 $kWh/m^3$ | 0.170 $kWh/m^3$ |
| Electricity (for MBR) | - | | 2.95 $kWh/m^3$ |
| Electricity (for AOP) | - | | 0.420 $kWh/m^3$ |

Life Cycle Inventory – Output with the functional unit as 1 $m^3$ of wastewater prior to entering the wastewater treatment system.

| Resource | Scenario 1 * | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Alkalinity | 85.0 $g/m^3$ | 54.2 $g/m^3$ | 57.1 $g/m^3$ |
| pH | 7.10 | 7.51 | 7.62 |
| Chemical Oxygen Demand | 1288 $g/m^3$ | 146 $g/m^3$ | 0.010 $g/m^3$ |
| Biological Oxygen Demand | 525 $g/m^3$ | 363 $g/m^3$ | 24.3 $g/m^3$ |
| Total Organic Carbon | 1570 $g/m^3$ | 160 $g/m^3$ | 0.160 $g/m^3$ |
| Total Suspended Solids | 686 $g/m^3$ | 103 $g/m^3$ | 1.03 $g/m^3$ |
| FGO | 183 $g/m^3$ | 4.80 $g/m^3$ | 4.80 $g/m^3$ |
| Total Nitrogen | 215 $g/m^3$ | 215 $g/m^3$ | 157 $g/m^3$ |
| Total Phosphorus | 33.5 $g/m^3$ | 33.5 $g/m^3$ | 0.000 $g/m^3$ |
| Sulphate | 622 $g/m^3$ | 622 $g/m^3$ | 617 $g/m^3$ |
| Nickel | 3.28 $g/m^3$ | 3.28 $g/m^3$ | 3.28 $g/m^3$ |
| Lead | 1.36 $g/m^3$ | 1.36 $g/m^3$ | 0.0300 $g/m^3$ |
| Zinc | 1.88 $g/m^3$ | 1.88 $g/m^3$ | 0.430 $g/m^3$ |
| Copper | 10.6 $g/m^3$ | 10.6 $g/m^3$ | 0.530 $g/m^3$ |
| Cadmium | 0.750 $g/m^3$ | 0.740 $g/m^3$ | 0.240 $g/m^3$ |
| Sludge | - | 0.510 $m^3_{sludge}/h$ | 1.37 $m^3_{sludge}/h$ |
| Sludge (normalised per functional unit) | - | 0.0124 $m^3_{sludge}/h/m^3$ | 0.0333 $m^3_{sludge}/h/m^3$ |
| Wastewater | 41.1 $m^3/h$ | 40.6 $m^3/h$ | 39.3 $m^3/h$ |

*Indicates experimental data, provided by an industrial unit

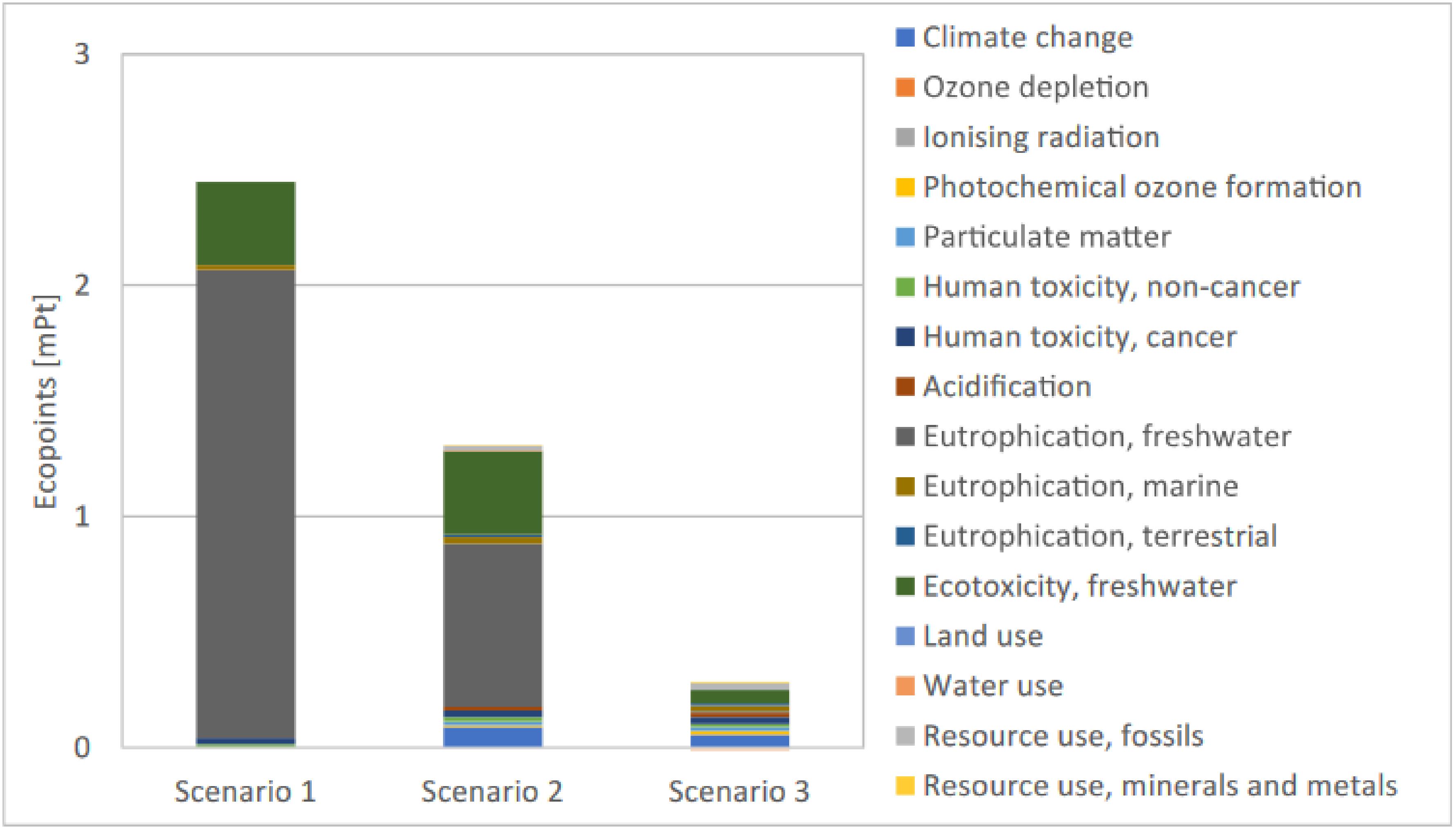
# Life Cycle Impact Assessment

Retrieval of Characterisation Factors

| Resource | Ecoinvent Entry |
|---|---|
| Citric Acid | 1 kg Citric acid {GLO}\| market for \| APOS, U (of project Ecoinvent 3 - allocation at point of substitution - unit) |
| Sodium Hypochlorite | 1 kg Sodium hypochlorite, without water, in 15% solution state {RER}\| market for sodium hypochlorite, without water, in 15% solution state \| APOS, U (of project Ecoinvent 3 - allocation at point of substitution - unit) |
| Electricity | 1 MJ Electricity, medium voltage {RO}\| market for \| APOS, U (of project Ecoinvent 3 - allocation at point of substitution - unit) |
| Water | 1 $m^3$ Water, deionised {Europe without Switzerland} \| market for water, deionised \| APOS, U |
| Sludge Treatment | 1kg Digester sludge {GLO}\| treatment of digester sludge, municipal incineration \| APOS, U |

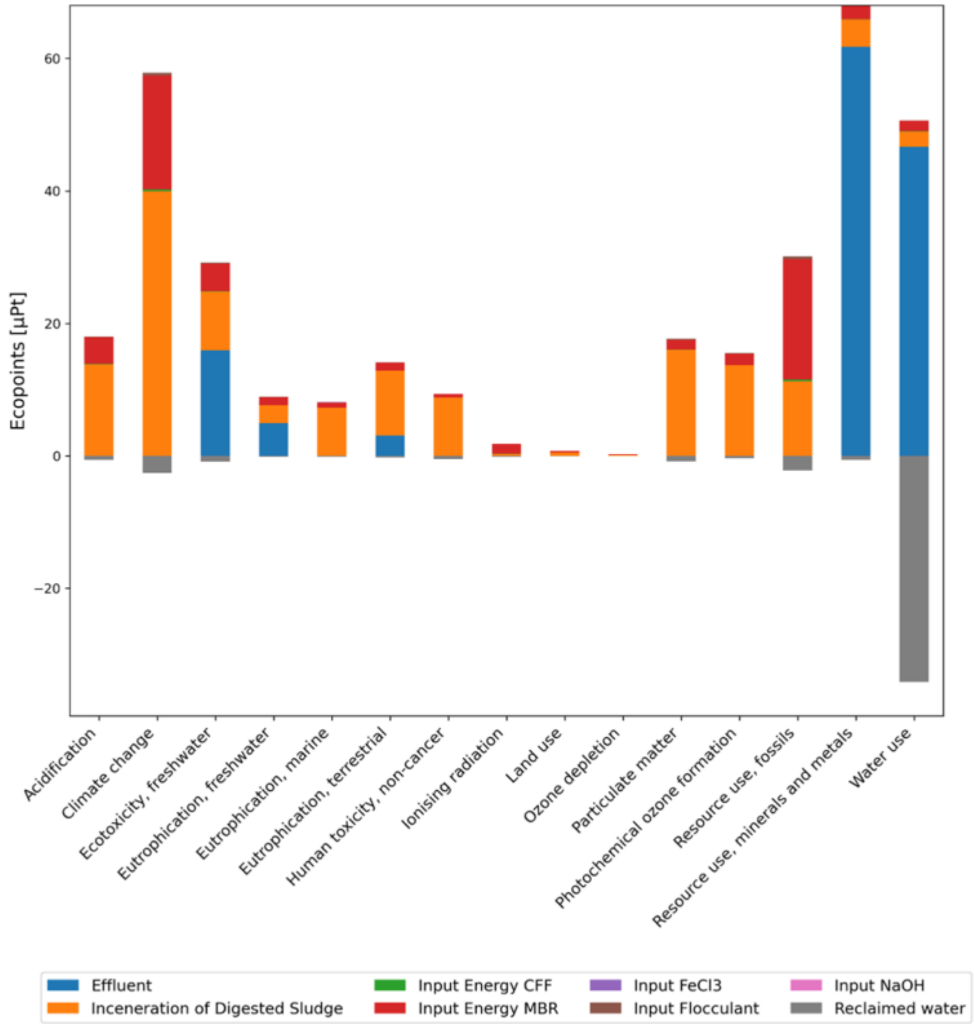
# Life Cycle Impact Assessment

Environmental Footprint Calculation



# Life Cycle Impact Assessment

Interpretation of Results



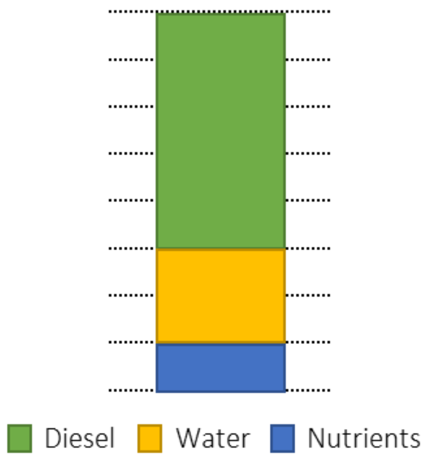

Finding the environmental hotspots, i.e. the processes/flows/stages with the highest contribution to the environmental impacts

Identifying further potential improvements to reduce the environmental impact

# What can Dynamic LCA offer?

## Identify Hot Spots

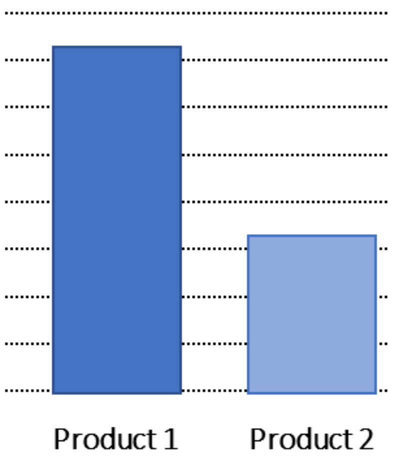
Identify the stage or the flow that is responsible for the higher share of environmental impact




*Breakdown of the environmental performance of process X*

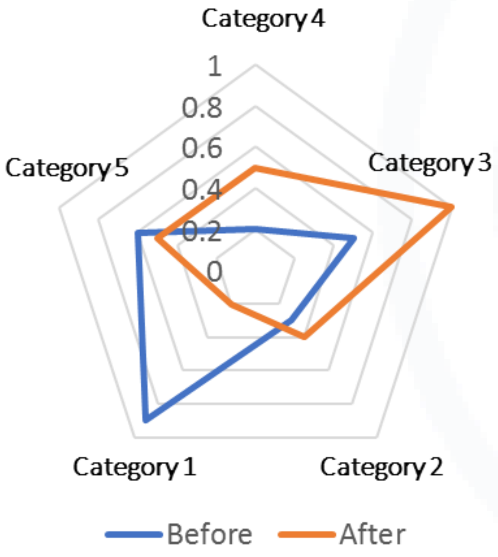
## Compare Alternative Processes/Products

Compare the environmental performance of two similar products, with different production methods




## Estimate the Consequences

Assess the environmental performance of a process before and after certain interventions




## Assess Impact Over Time

Monitor or estimate the environmental impact variation over time, under different assumptions