OSMOSE-Lua – A Unified Approach to Energy Systems Integration with Life Cycle Assessment

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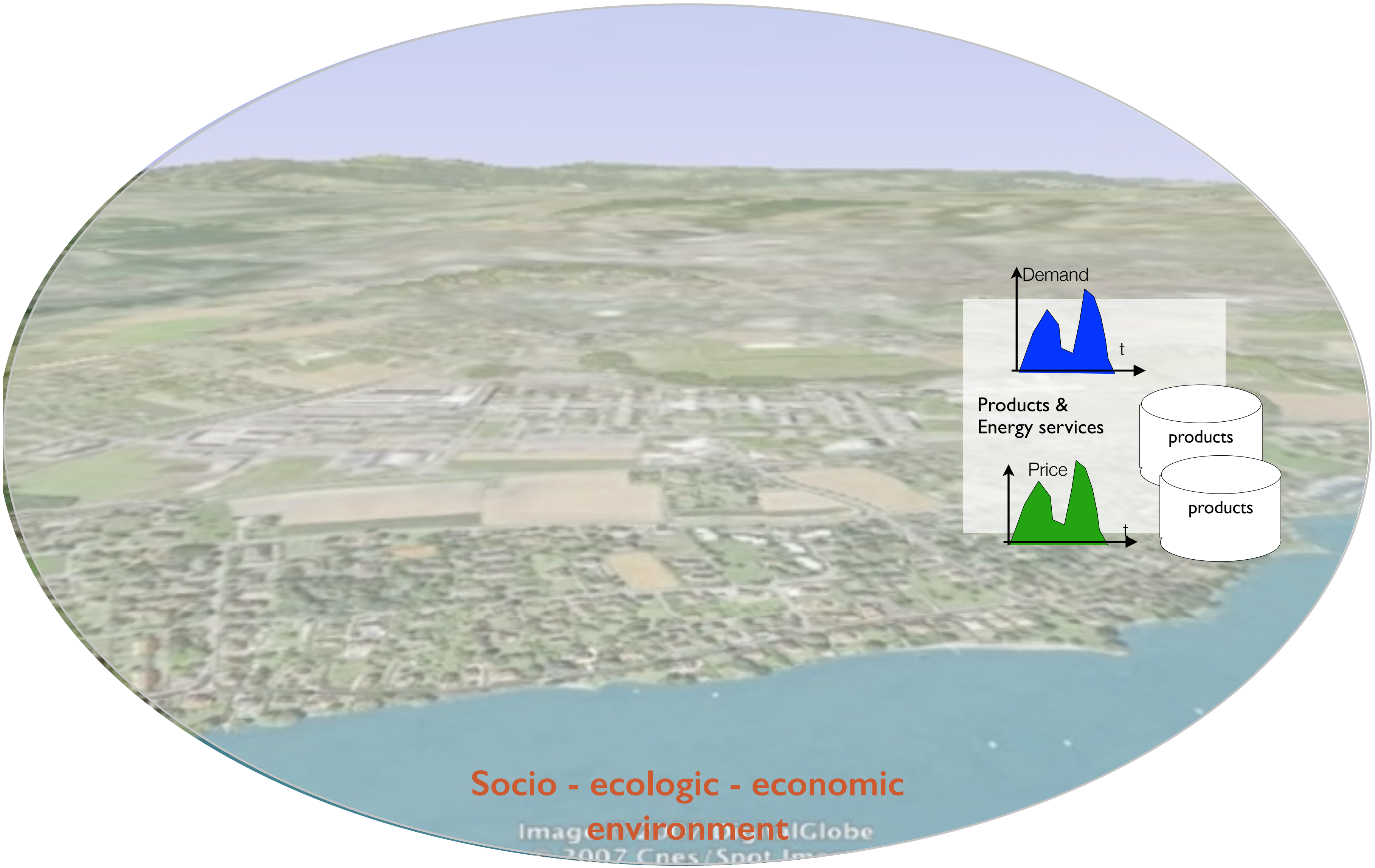
The system vision of the energy usage

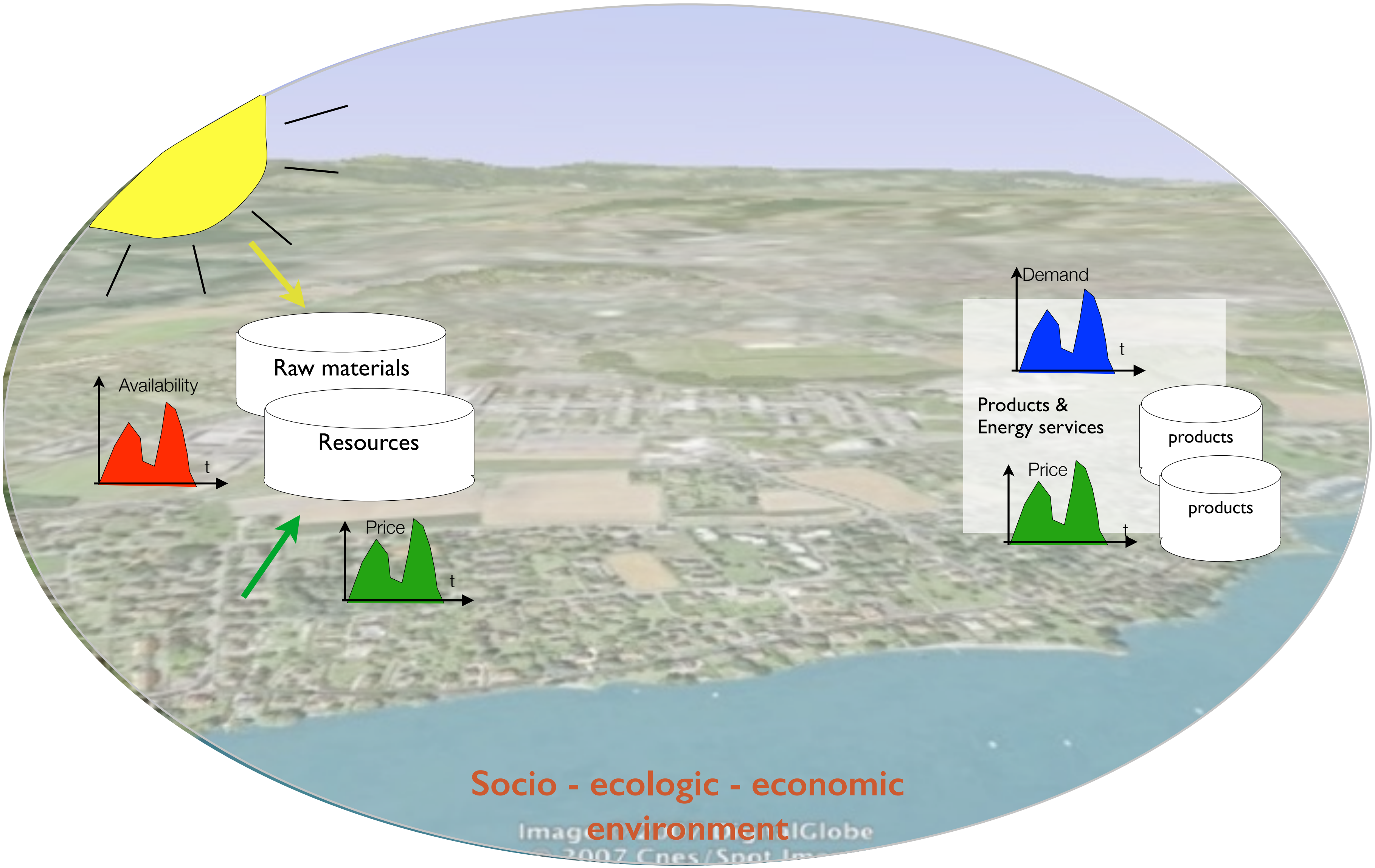
The system vision of the energy usage

Socio - ecologic - economic environment

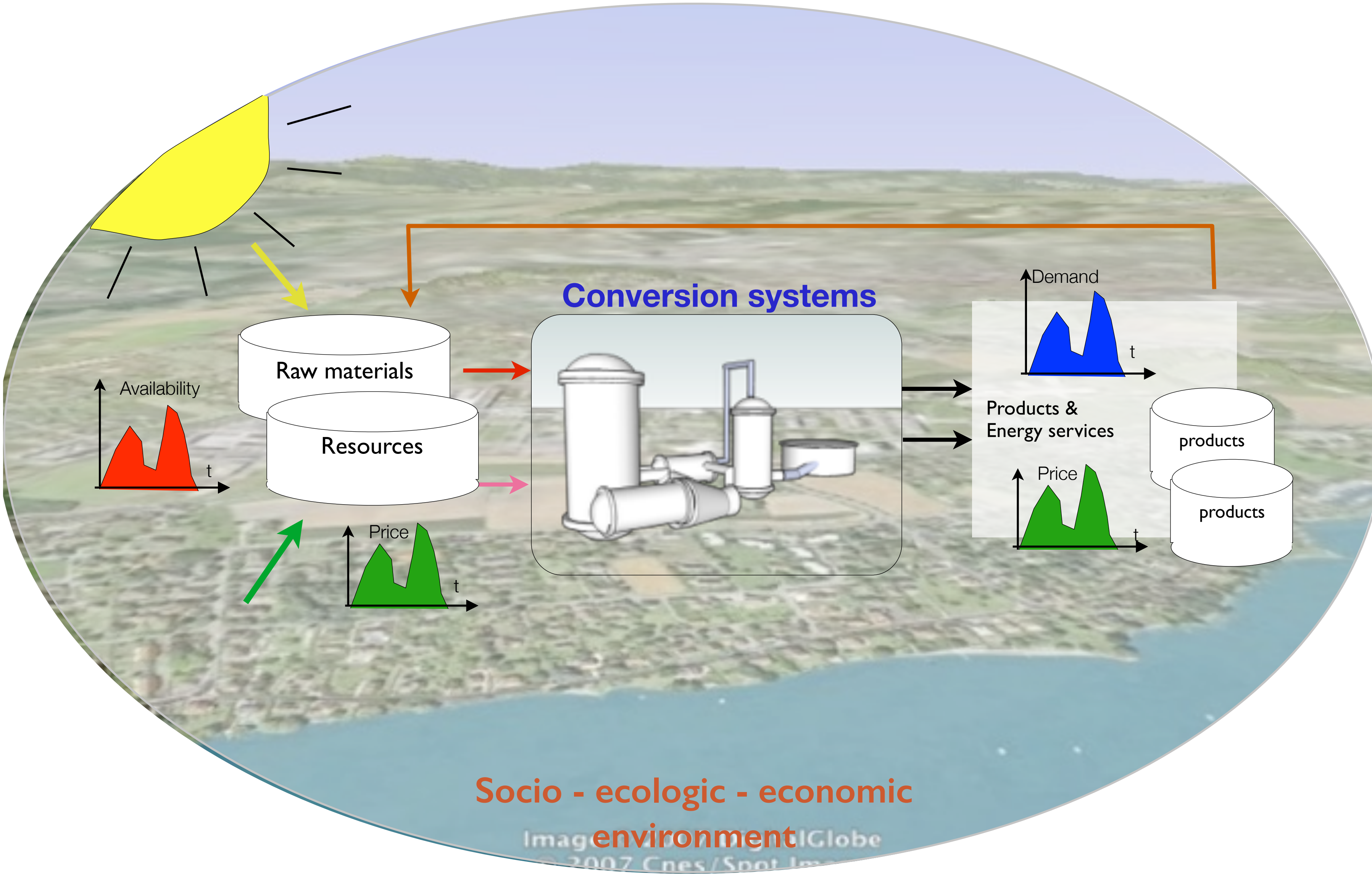
The system vision of the energy usage



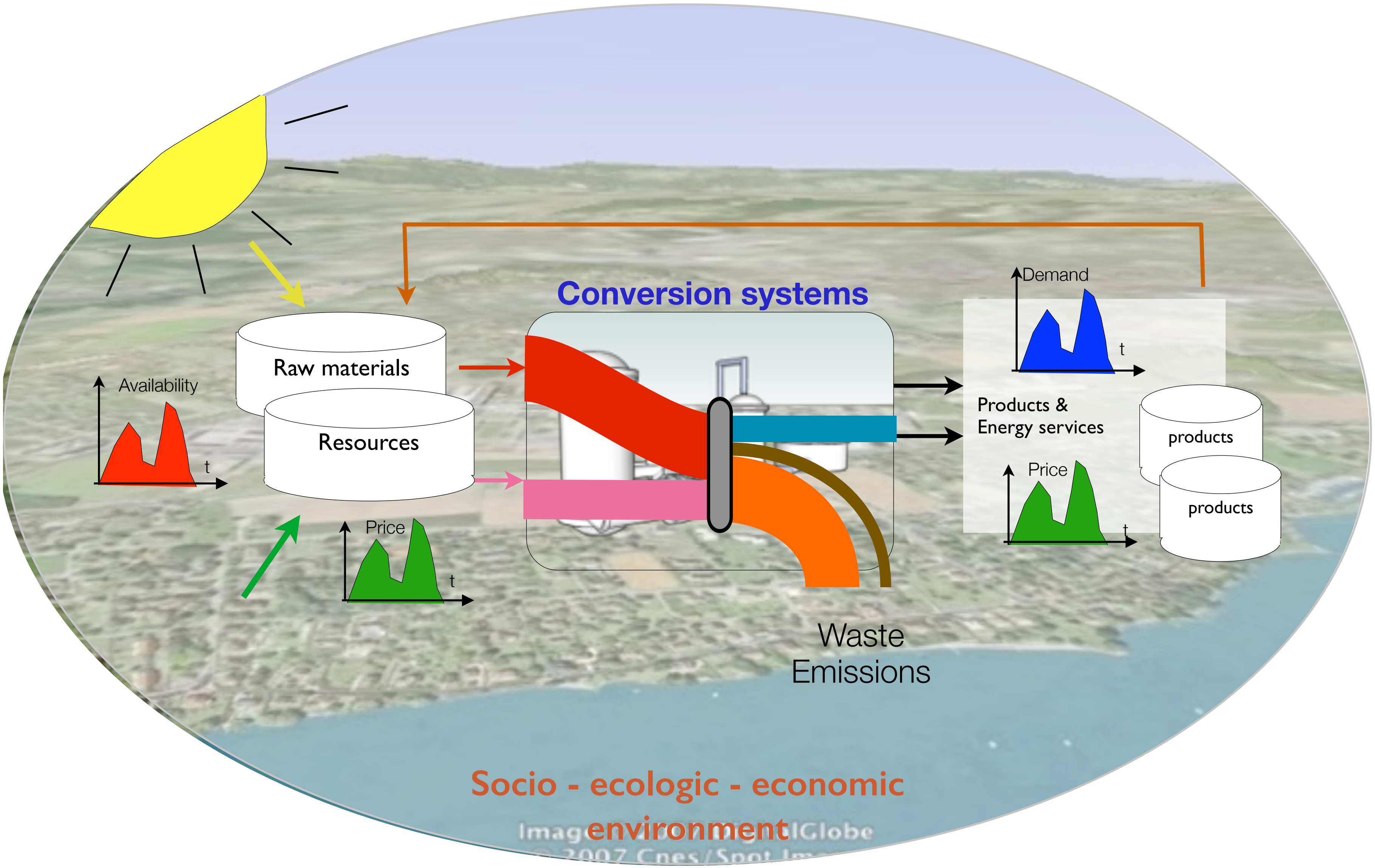
The system vision of the energy usage



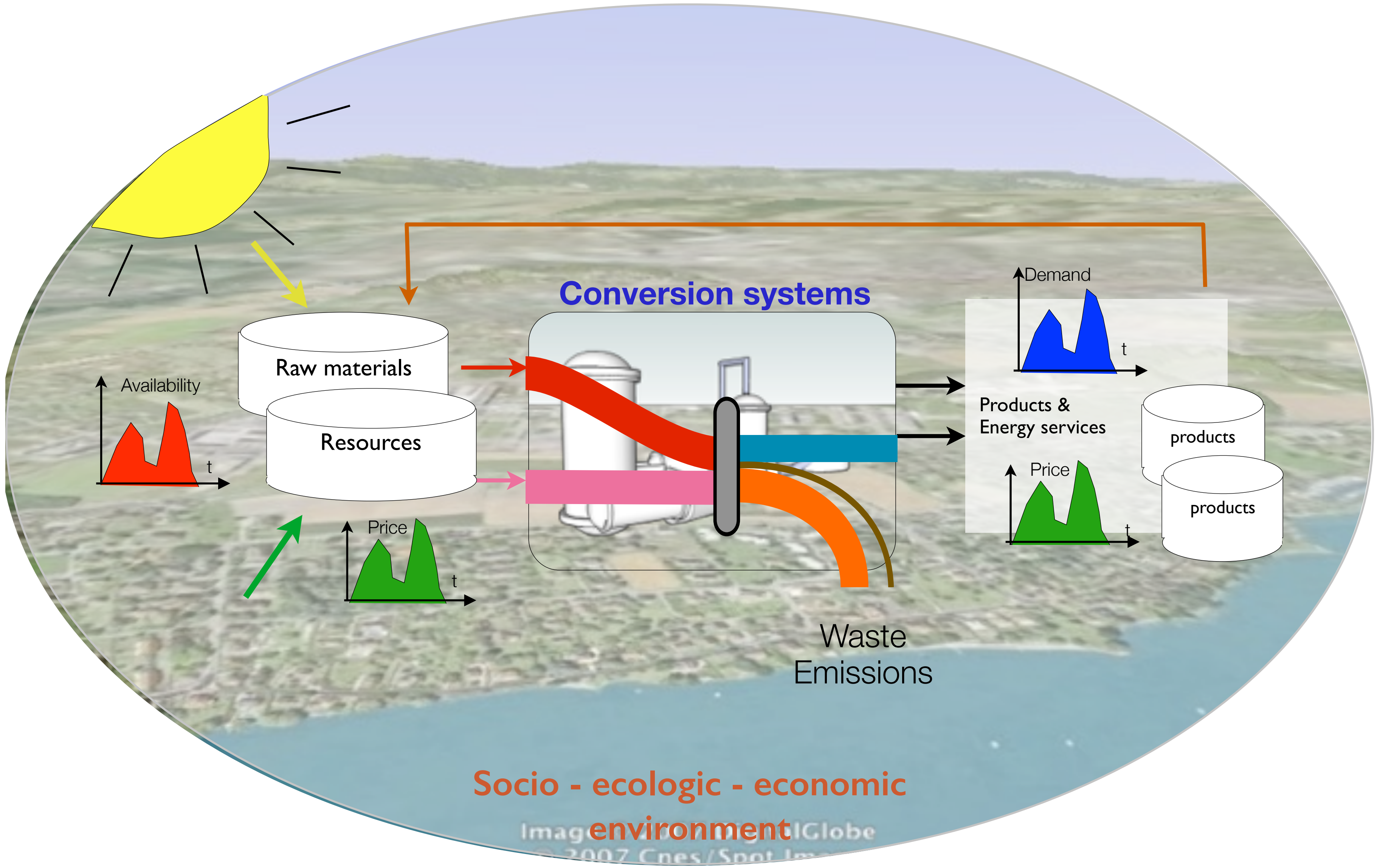
The system vision of the energy usage



The system vision of the energy usage



Energy system design



Problem definition

- Characterise and localise the technologies to be used to supply the energy services and the products needed over the lifetime of the system's element at the time they are needed with the resources that are available
  - Decisions to be taken
    - Technology : choice, size and location — $Y_{u,l}, S_{u,l}$
    - The operating strategy — $f_{u,l,t(p)} \quad \forall p, u, l$
    - The services that are provided — $f_{u \rightarrow s,l,t(p)} \quad \forall p, u, l, s$
    - The resources that are used — $f_{r \rightarrow u,l,t(p)} \quad \forall p, u, l, r$
  - Criteria
    - Minimum cost = OPEX + APEX
    - Maximum profit = NPV (i,lifetime,cost)
    - Minimum environmental impact = LCIA
    - Max renewable energy integration
  - Constraints
    - Mass & Energy Balances
    - Context specs
    - Bounds

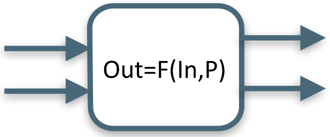
The energy systems engineering methodology

Energy services
Resources
Context & Constraints

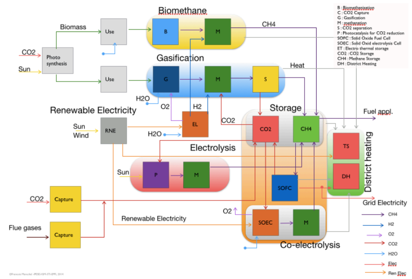
System Boundaries

Technology options

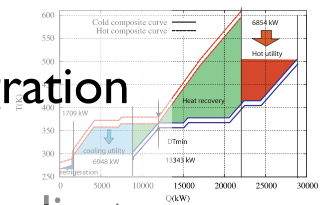
Models



Superstructure



Heat &
Mass integration

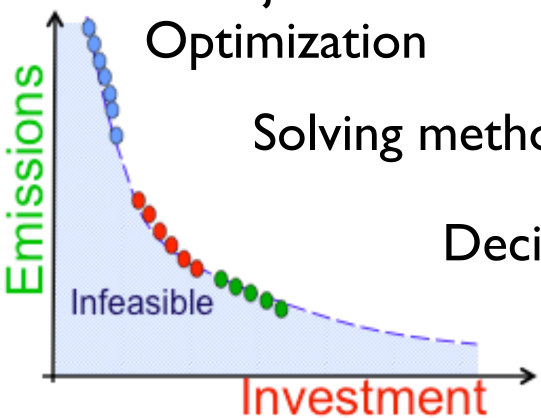


System performances indicators
- Economic
- Thermodynamic
- Life cycle environmental impact

Decision variables

Solving method

Multi-objective
Optimization



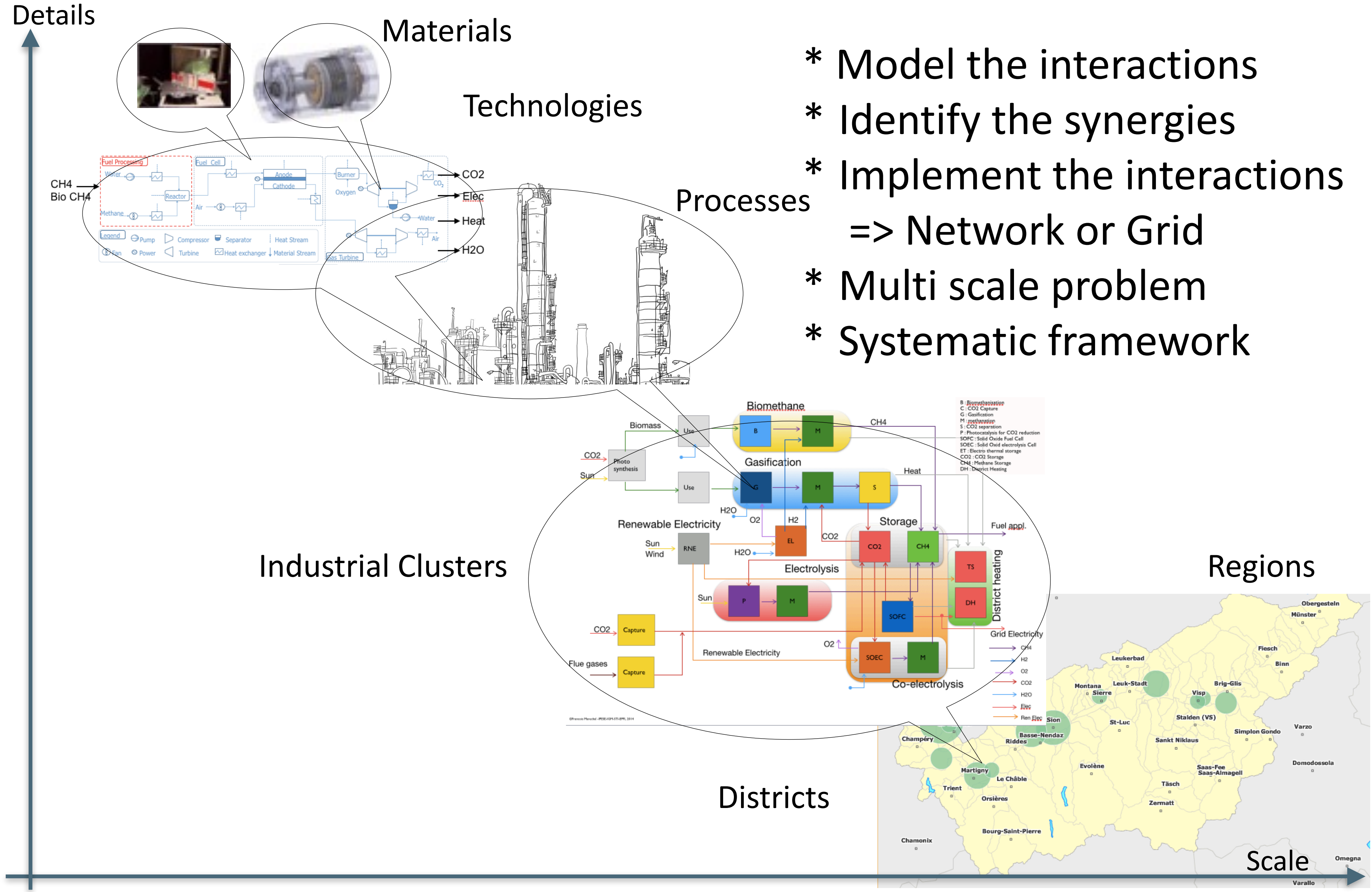
Thermo-economic Pareto

Results analysis
- Exergy analysis
- Composite curves
- Sensitivity analysis
- Multi-criteria

Solutions

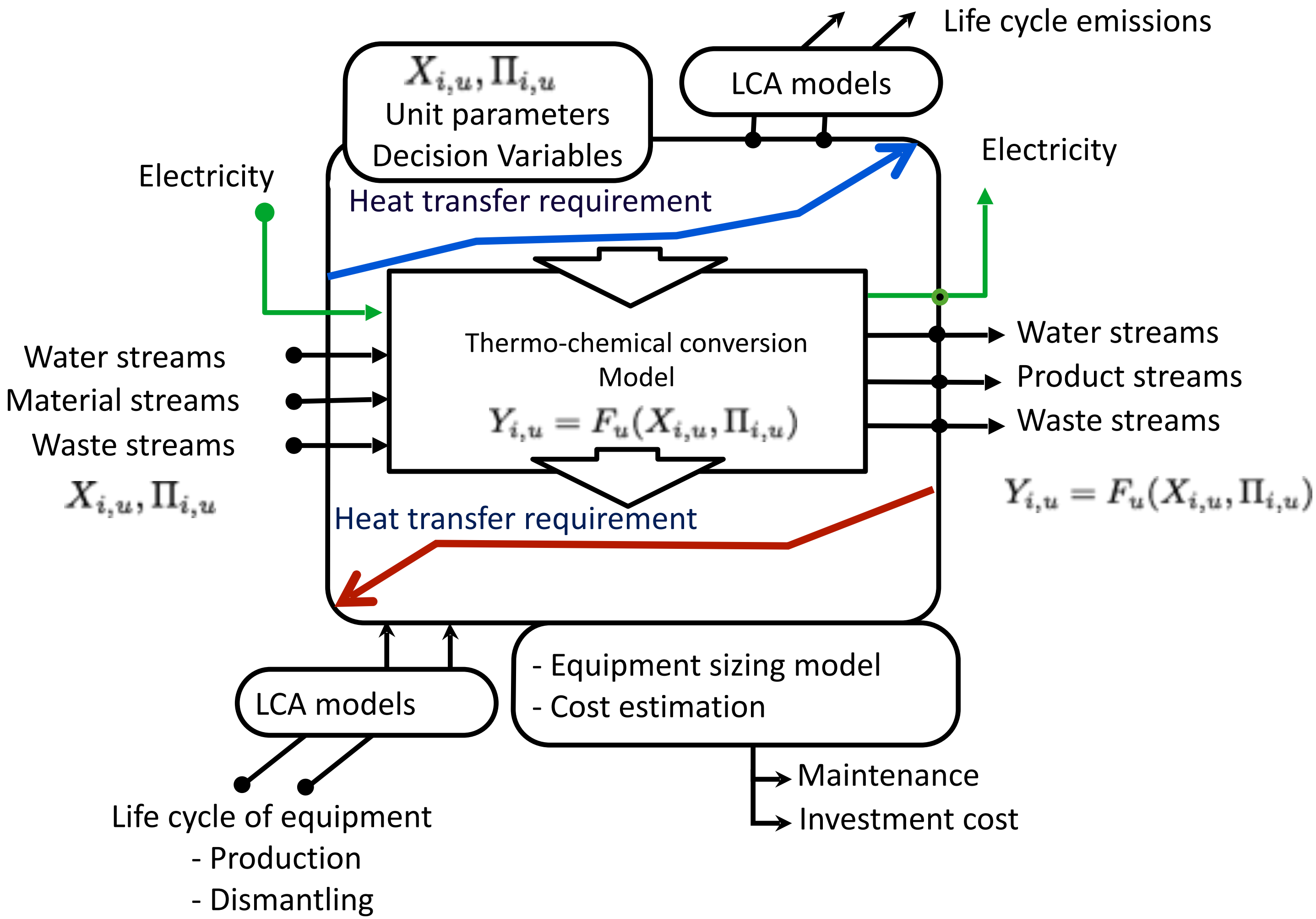
Energy systems integration : multi-scale problem

* Model the interactions
* Identify the synergies
* Implement the interactions
  => Network or Grid
* Multi scale problem
* Systematic framework



The energy technology building block

- Model of the interconnectivity (mass, heat, energy)
- Model of the emissions (Equipment, Emissions)
- Model of the cost (size => cost, maintenance)

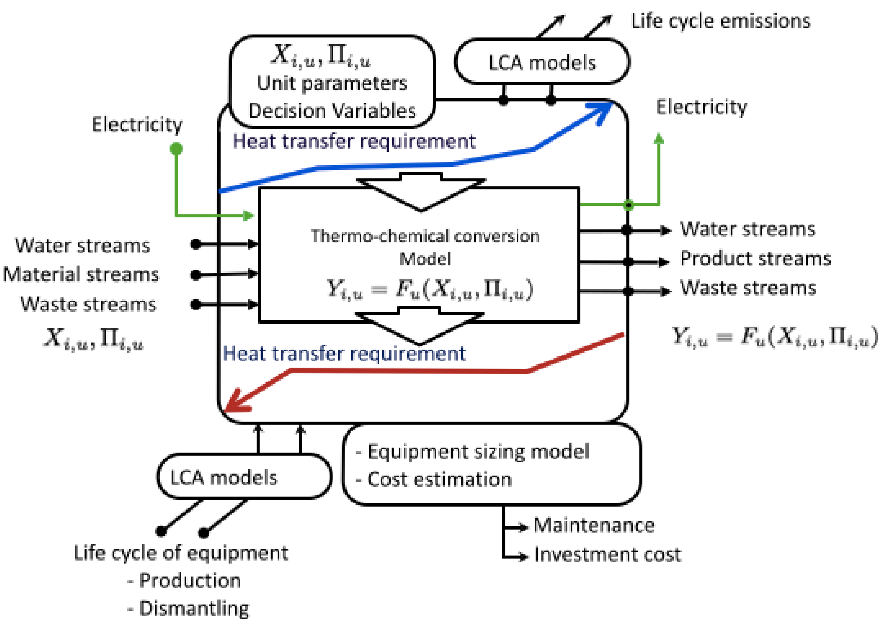


Energy technology approach

- Advantages
  - Expert developed model
    - Flowsheeting model and tool
    - Level of detail
  - Independent of the energy systems integration
  - Model data base can be developed
- Difficulties
  - Remote access of models
    - Use of surrogate models
  - Consistency of the models in the energy systems
    - from black box to white box
  - Model data base
    - Confidence for reusing the models
    - Documentation
    - Certification of the model quality

Energy Technologies Encapsulation

Common interface of a module for system integration



Unit documentation
- Description
- Purpose
- Limitation
- Authors

Model
Data base

Unit connectivity
- Layers connections

Layer ontology
Data base

Unit execution handler
- Input data
- Calculation engines
  - Existing flowsheeting software
  - Mimetic models
- Output data
  - Integration/interconnectivity
  - Costing
  - LCA => Ecoinvent LCI

Flowsheeting tools
- BELSIM-VALI
- gPROMS
- ASPEN plus
- HYSYS
- Matlab
- Simulink
- (CITYSIM)
- MODELICA
- Others possible
  - CAPE-OPEN ?
  - PROSIM

Unit model report
- Summary of results
- Important data
- Errors
- Validity

Knowledge
Data base

Model encapsulation Model ontology

Ontology of a value in OSMOSE LUA

$$\dot{m}_{u,l}(t), Y_{i,u,l}(t), X_{i,u,l}(t), \Pi_{i,u,l}(t), KPI_k, \dot{m}^*_{u,l}, Y^*_{i,u,l}, X^*_{i,u,l}, \Pi^*_{i,u,l}$$

A variable is the smallest data structure handled by OSMOSE. A variable is defined by

1. **Name** or **tagname** that litteraly identifies the variable
2. **ID** that is tagging the variable
3. **Parent** indicates the module to which the variable belongs
4. **Value** that defines one instance of the variable => Matrix
   A priori value of the variable will exist for any **time** in the **time sequence**, for any **period** and for any **scenario** in which the system is calculated.
5. **MinimumValue** and a **MaximumValue** that defines the bounds for the value of the variables
6. **DistributionType** and **DistributionParameters** that defines the uncertainty of the value
7. **DefaultValue** that defines the value of the variable when it is created. this is also the recommended order of magnitude of the value recommended for the calculations
8. **PhysicalUnit** that defines the physical unit of the value of the variable
9. **DefaultPhysicalUnits** that defines the physical unit with which the calculation have to be made, It means that a preprocessing phase will have to convert the value from the **PhysicalUnits** to the **DefaultPhysicalUnits** as well as a post-processing phase that is going to convert from the **DefaultPhysicalUnits** to the **PhysicalUnits** .
10. **Status** that identifies if the variable has a fixed value or a value that will be calculated. The status should identify as well if the value is calculated for each time or if it is constant or if it requires recalculation for each time. Status is equivalent to *ISVIT* in OSMOSE.
    - i **x** : value is unique for the scenario (i.e. 1 value/scenario)
    - ii **x0** : value is period dependent (i.e. 1 value/period and / period)The value may calculated during preprocessing phase using the model (i.e. constant that is period dependent).
    - iii **x00** : the value is time dependent (i.e. 1 value/time and period and scenario).

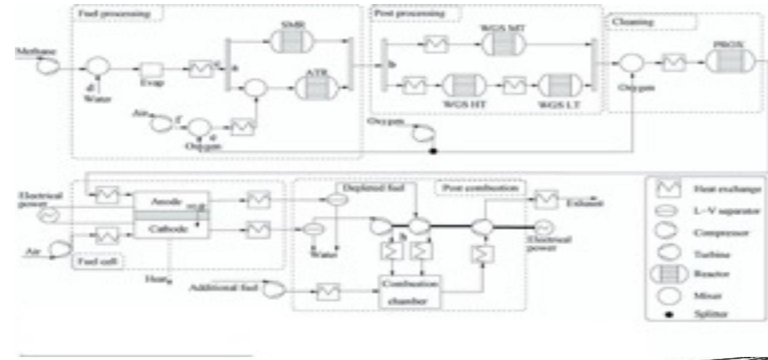
      where **x** =

```
 1 : for constant to be fixed by the user or the optimizer
 2 : for constant fixed by the user or the optimizer otherwise use the default value
-1 : for values calculated by the model
```

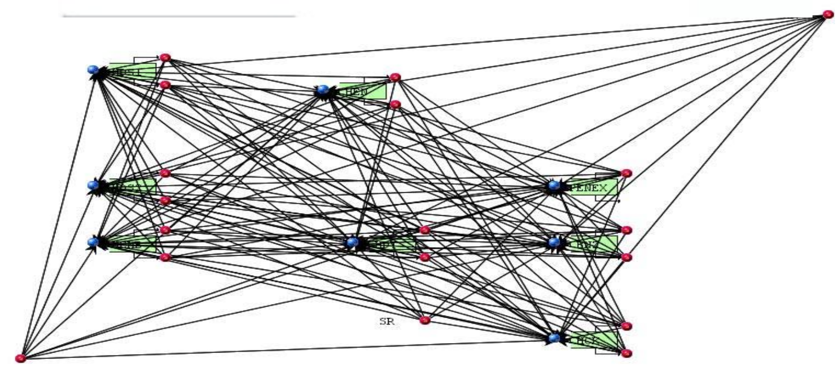
11. **Dependence Matrix** a dependence matrix that identifies the dependence of the value with respect to the other values of the problem is stored. Each of the dependence includes the mention if the dependence is **linear**, in which case the value of the dependence is stored in the field as a couple (ID,numerical value), or it can be stored as a reference to a non linear dependence that could be a surrogate model or the access to the model that calculates the dependence.

Superstructure definitions

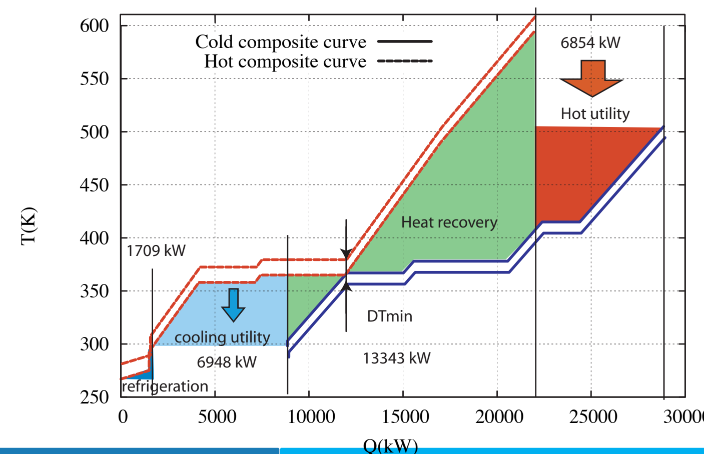
- Explicit
  - In flowsheeting software



- Automatic
  - Based on the connectivity description
  - Restricted matches
  - Routing

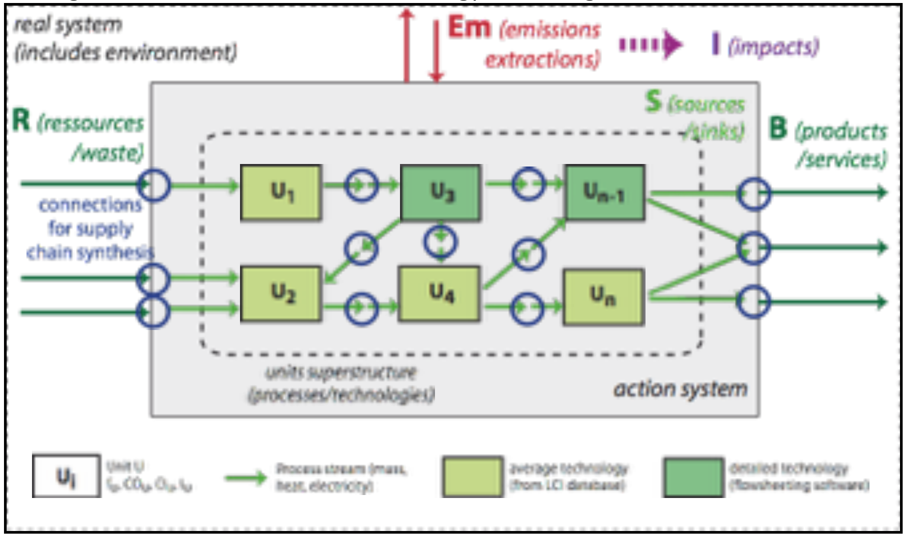


- Implicit
  - Heat cascades
- Combined
  - Mass and Energy



Geograhical information

At a given location : combination of energy technologies



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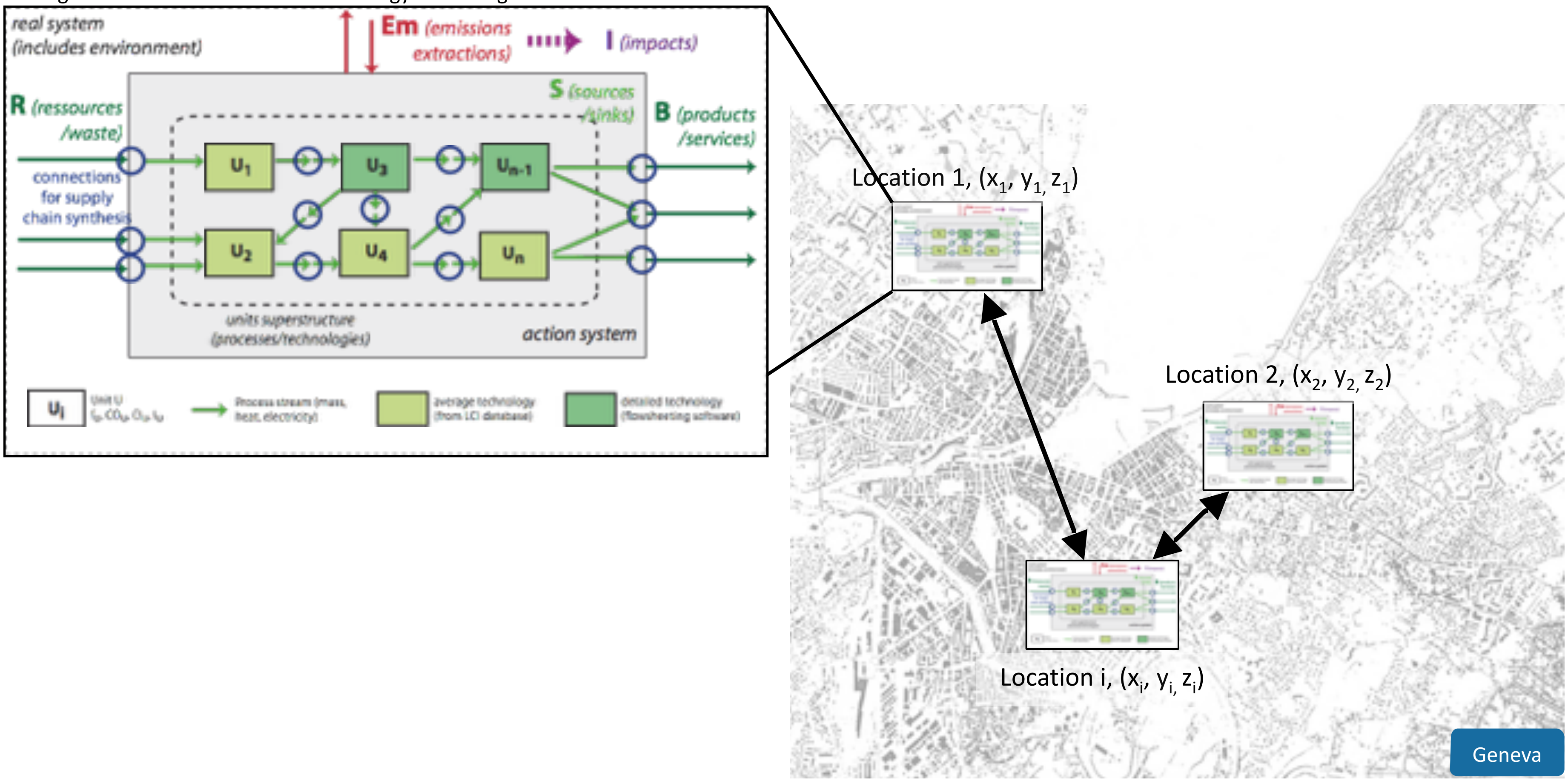

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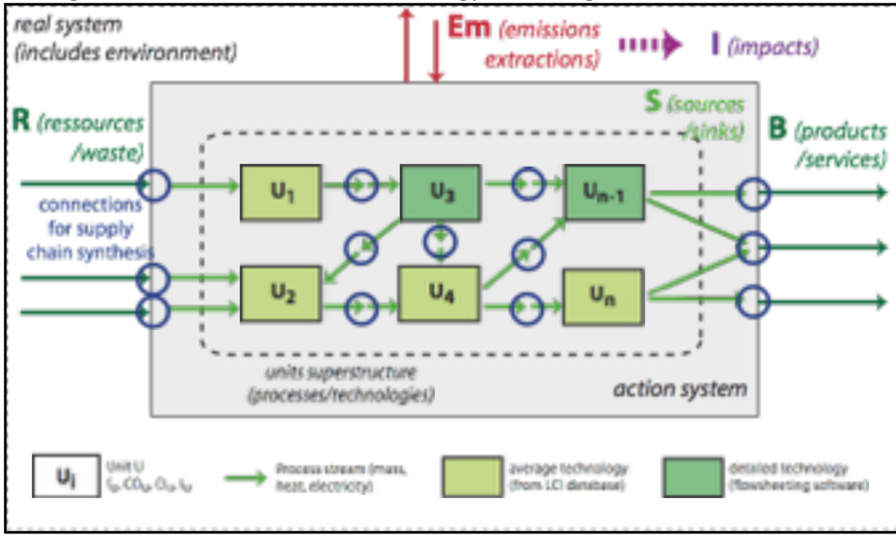

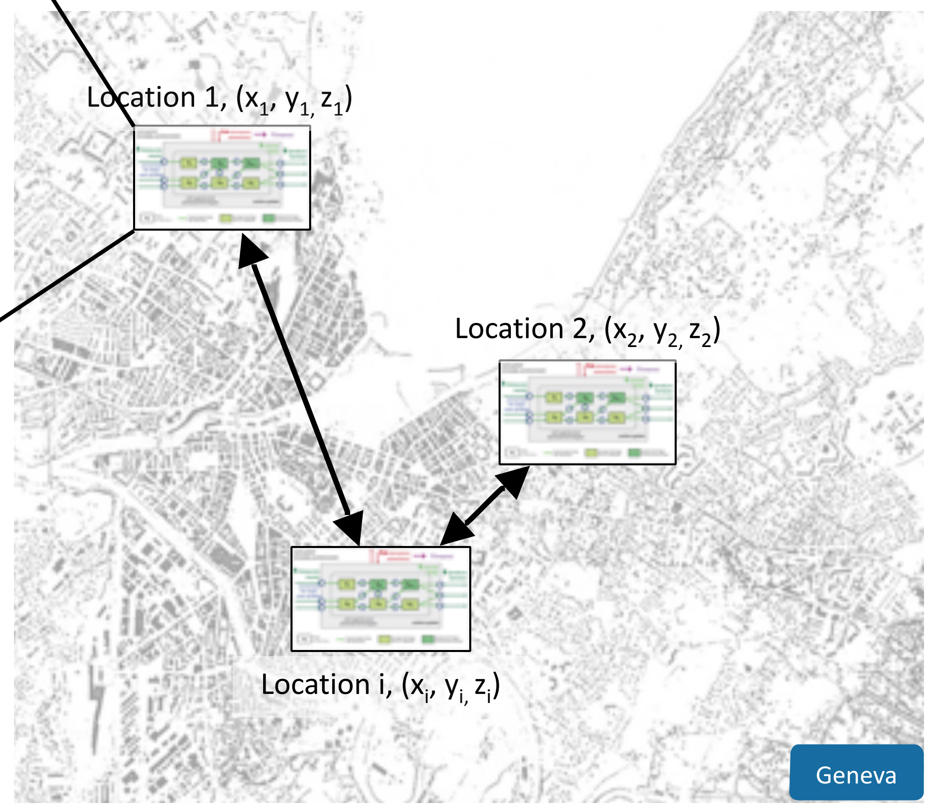

- **Coordinates attributed to locations**
  - GIS data base => POSTGRE SQL
  - GIS Level of details
    - Roads, district heating network, electricity grid
  - GIS Tools : Routing, Layers, Representations
  - GIS Data
    - Buildings
    - Resources
    - Topology

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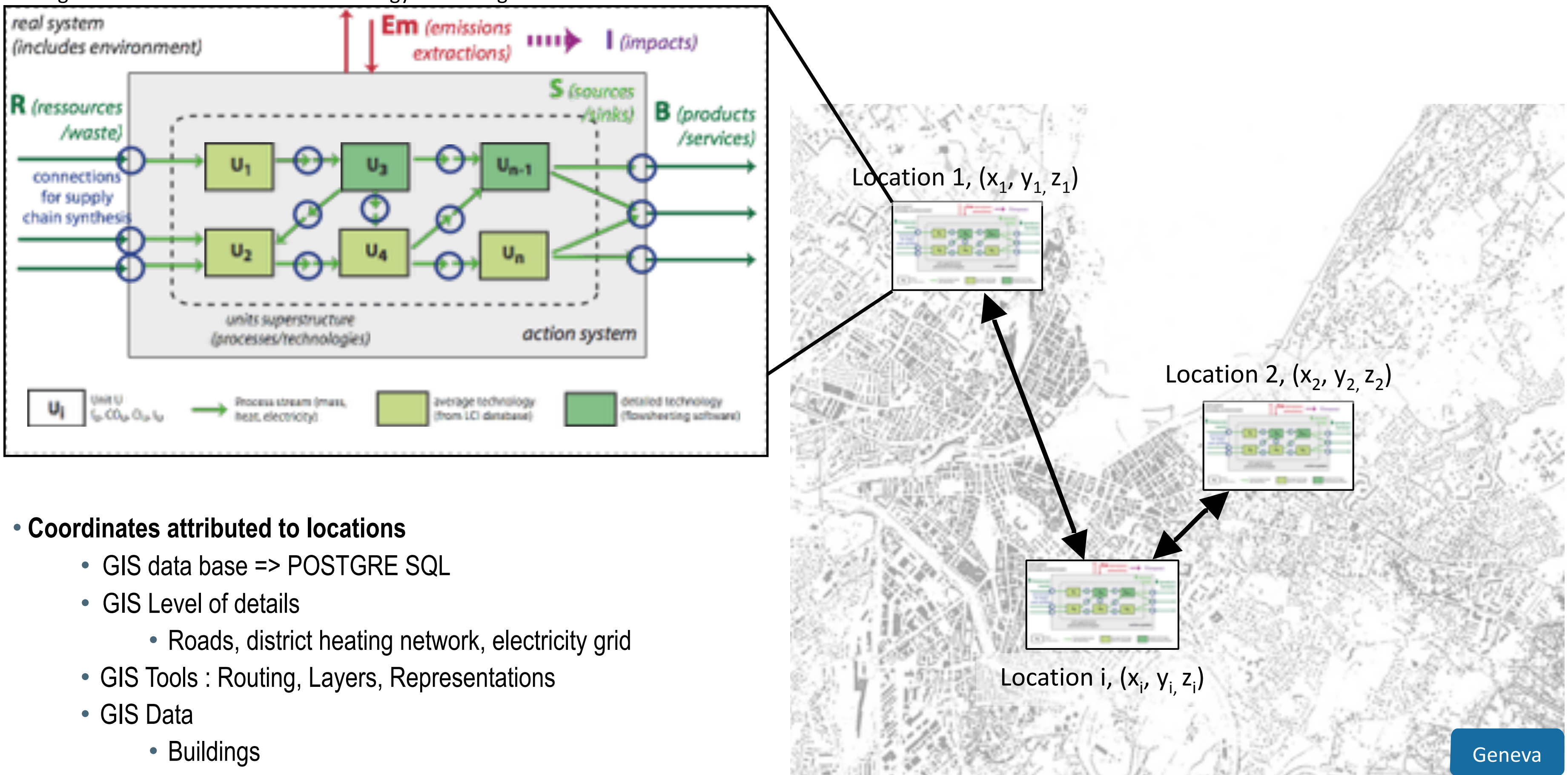

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- **Link between GIS data and Models**
  - Link with unit models parameters
  - Access to GIS tools in the workflow

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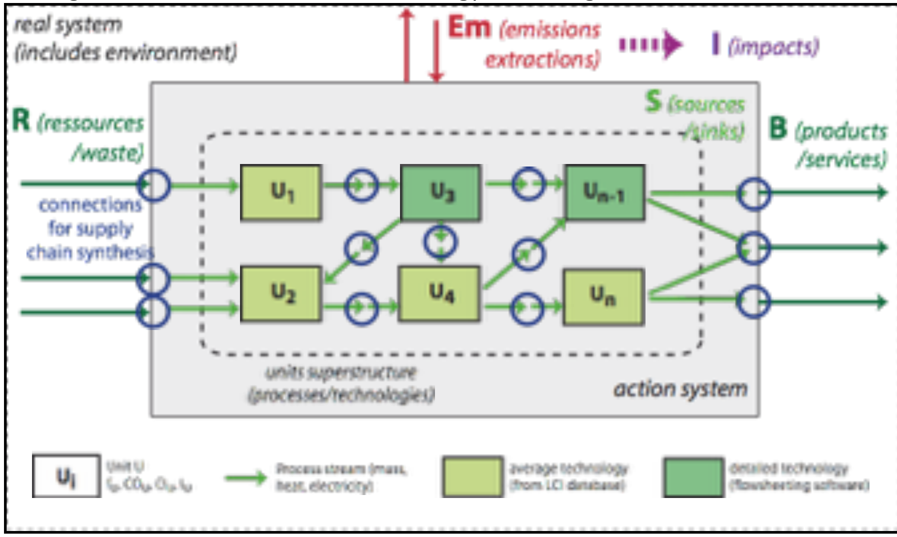

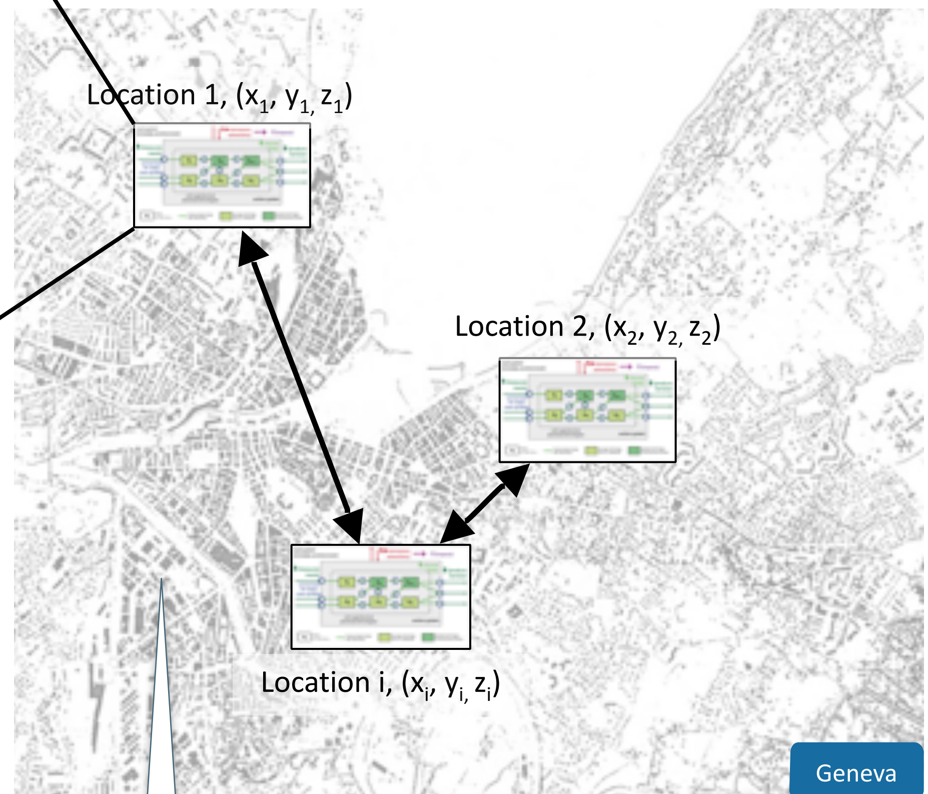

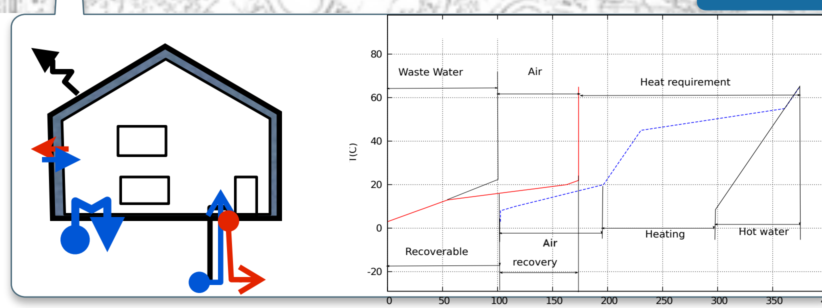

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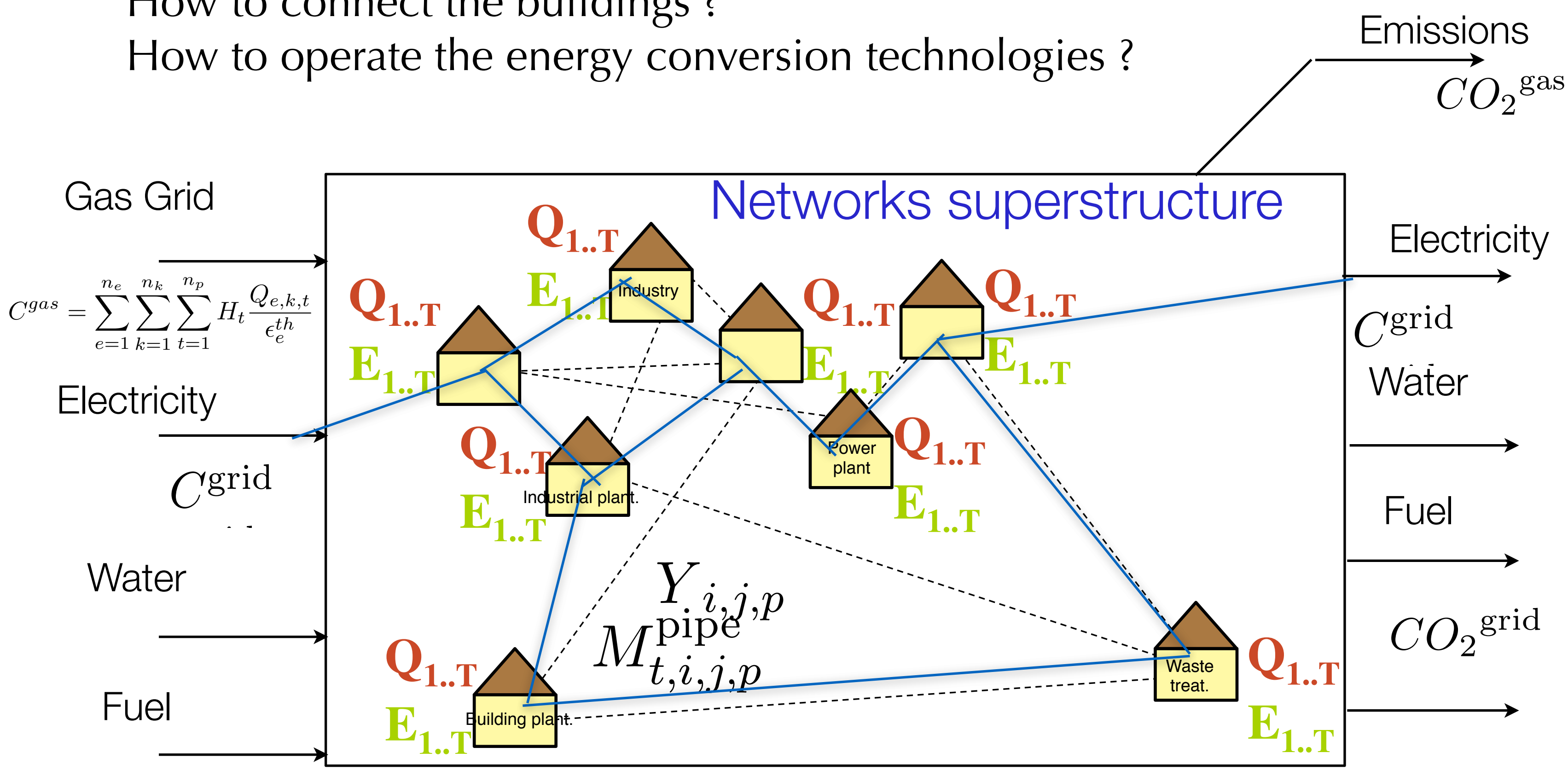
Energy system design : problem definition

Given a set of energy conversion technologies :

- Where to locate the energy conversion technologies ?
- How to connect the buildings ?
- How to operate the energy conversion technologies ?



Investment

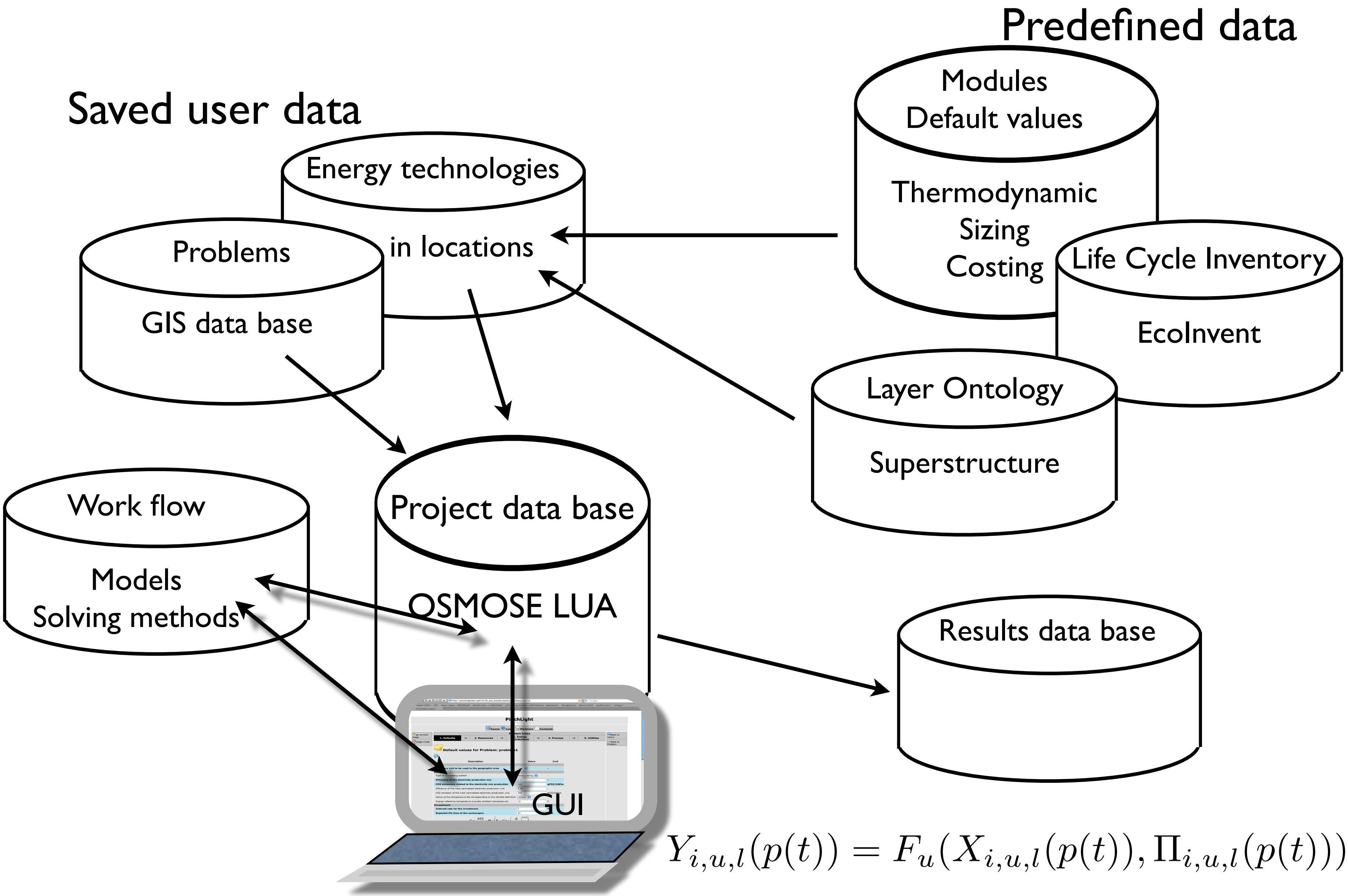
C^{pipes}

Maintenance

$$C^{inv} = \sum_{e=1}^{n_e}\sum_{k=1}^{n_k} a_e + a_e * S_{e,k}$$

[5] Francois Marechal, Celine Weber, and Daniel Favrat. Multi-Objective Design and Optimisation of Urban Energy Systems, pages 39–81. Number ISBN: 978-3-527-31694-6. Wiley, 2008.

Project data base



$$Y_{i,u,l}(p(t)) = F_u(X_{i,u,l}(p(t)), \Pi_{i,u,l}(p(t)))$$

MILP process integration model @location k

Technologies w, @location k period s and time t(s)

Demand @location k, period s and time t(s)

Subject to : Heat cascade constraints

Heat exchange by heat cascade model

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1, ..., n_r$$

Feasibility $R_r \geq 0 \qquad \forall r = 1, ..., n_r; R_{n_r+1} = 0; R_1 = 0 \qquad E^+ \geq 0; E^- \geq 0$

Electricity balance

Electricity consumption

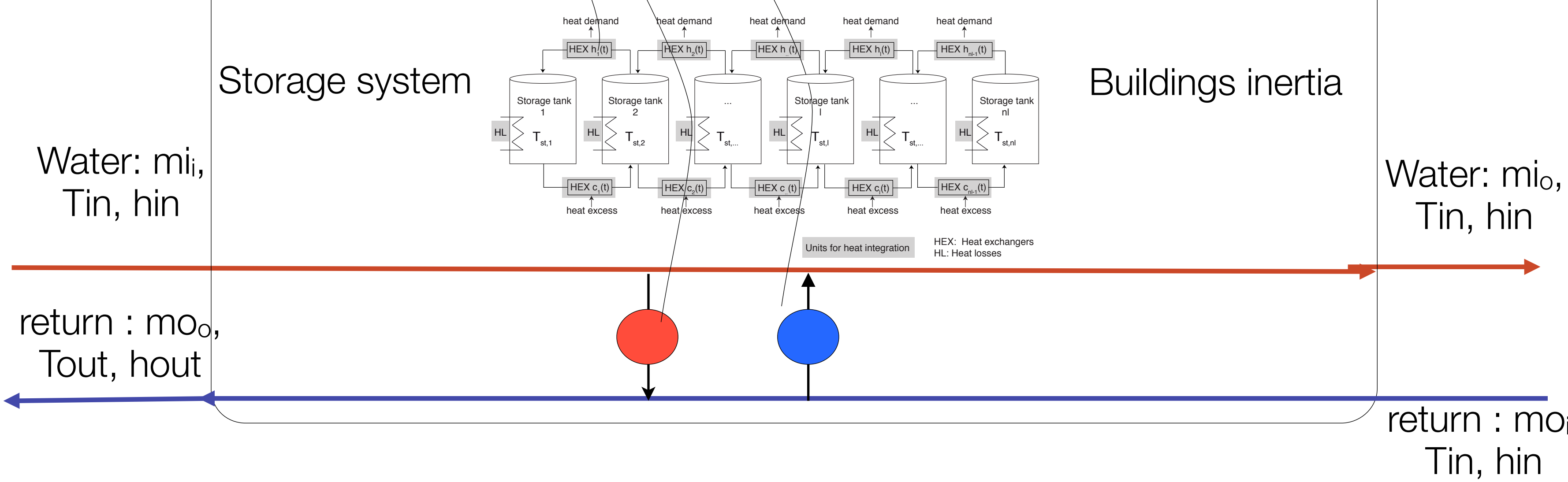
$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c \geq 0$$

Electricity production

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

Energy conversion Technology selection

Existence : w in location k $\quad fmin_w y_w \leq f_w \leq fmax_w y_w \qquad y_w \in \{0, 1\}$

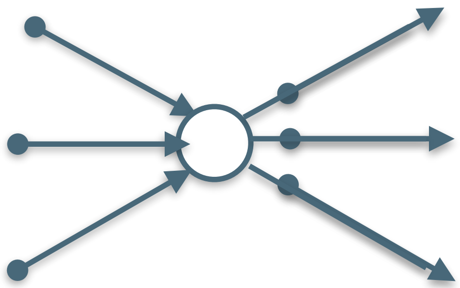


S. **Fazlollahi**, G. Becker and F. Maréchal. Multi-Objectives, Mul.-Period Optimization of district energy systems: II-Daily thermal storage, in Computers & Chemical Engineering, 2013a

Layers models / automatic superstructure

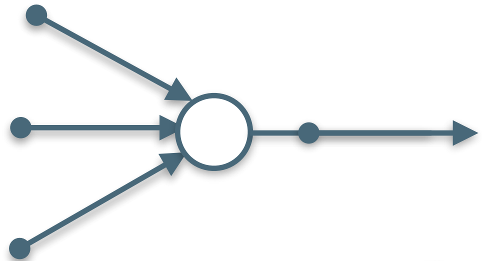
- Mass balance

$$\sum_{u=1}^{n_u}\sum_{l=1}^{n_l} k^{+}_{u,l,t} \cdot f_{u,l,t(p)} = 0 \quad \forall t(p) \quad \forall p$$

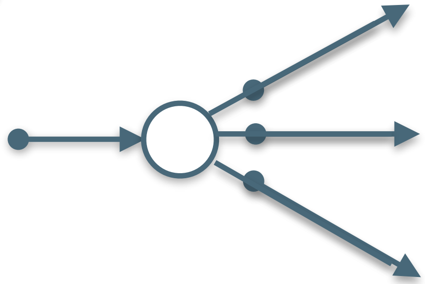


- Mass/heat distribution

$$\sum_{u=1}^{n_u} k^{+}_{u,l,t} \cdot f_{u,l,t(p)} = \sum_{j=1}^{n_l} e_{u,l,j,t(p)} \quad \forall t(p) \quad \forall p \forall l$$



$$\sum_{u=1}^{n_u} k^{-}_{u,l,t} \cdot f_{u,l,t(p)} = \sum_{j=1}^{n_l} e_{u,j,l,t(p)} \quad \forall t(p) \quad \forall p \forall l$$



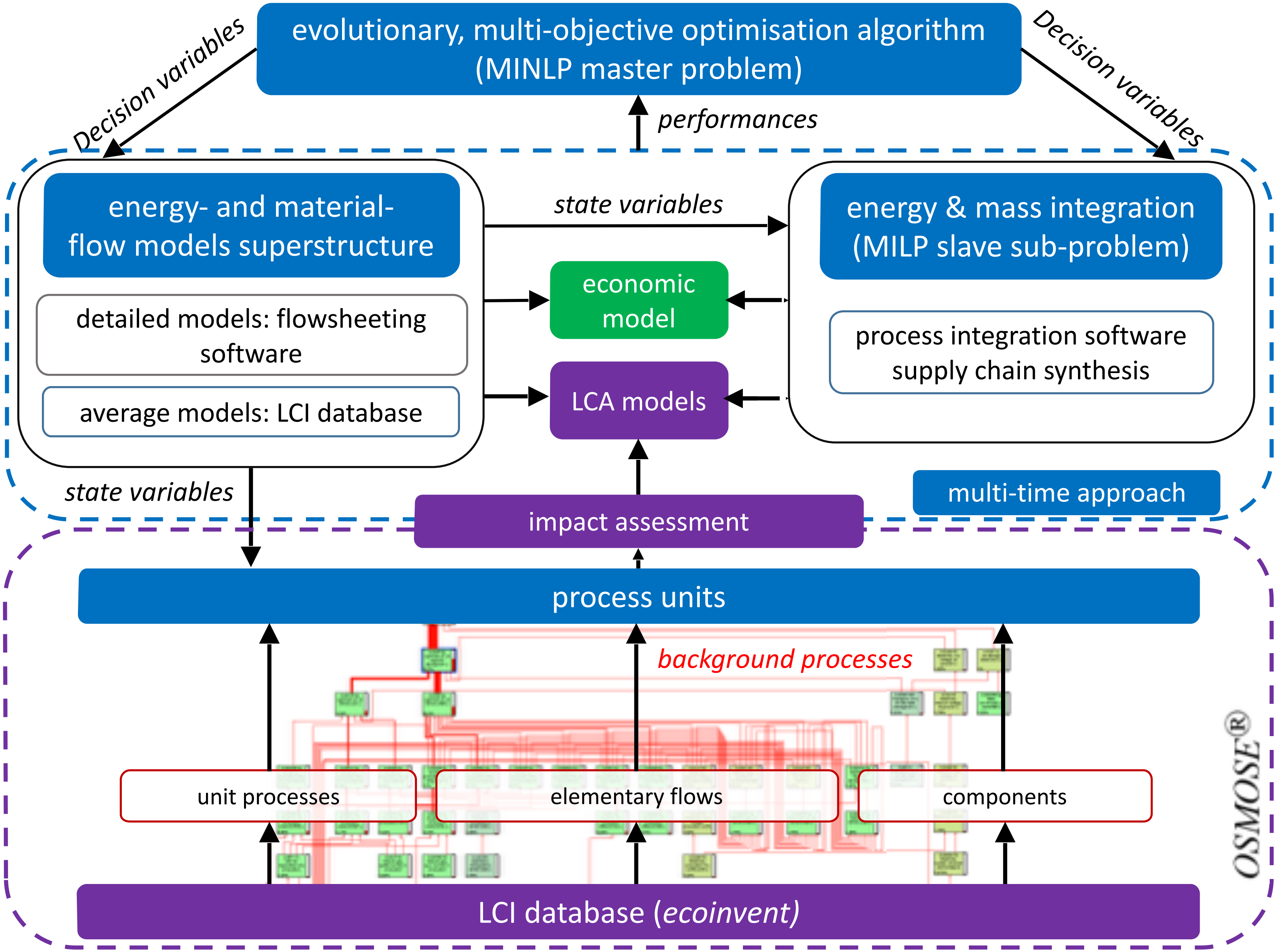
Process integration models

- **MILP (Mixed Integer Linear Programming) models**
  - Integer => Selection/Usage
  - Continuous => Level of usage in t(period)
  - Parametrised (T)
    - Discretisation
    - Decomposition
- **Applications**
  - Utility integration (Papoulias et al. , 1983, Marechal, et al., 1991)
    - Combined Heat and Power + Steam network (Marechal et al. , 1997)
    - Refrigeration Cycle (Marechal et al., 2000)
    - ORC systems (Bendig, 2015)
  - Multi-period (Marechal et al., 2003)
  - Multi period + Multi time (Weber et al., 2008)
  - Multi period + Multi time + Storage (Fazlollahi et al., 2012)
  - Multi period + Multi time + Multi-location+Storage (Fazlollahi et al., 2014)
  - Multi period + Multi time + Multi-location+Storage+Seasonal Storage (Rager et al., 2015)
  - Bio-refineries (Ensinas, 2015)
  - Industrial ecology (Gerber, 2013)
  - Restricted Matches (Becker et al., 2012)
  - Heat and Mass (Kermani et al., 2014)
  - Heat load distribution (Marechal et al., 1989)
  - Heat load Distribution multi-period (Mian et al. , 2014)
  - Heat load Distribution site scale (Pouransari et al., 2014)
  - Hydrogen Network (Girardin et al., 2006)
- MINLP (Mixed Integer Non Linear Programming) models
  - Heat Exchanger Network Design (Grossmann et al., Mian et al, 2014)
  - Heat Exchanger Network Design Multi-period (Mian et al., 2014)

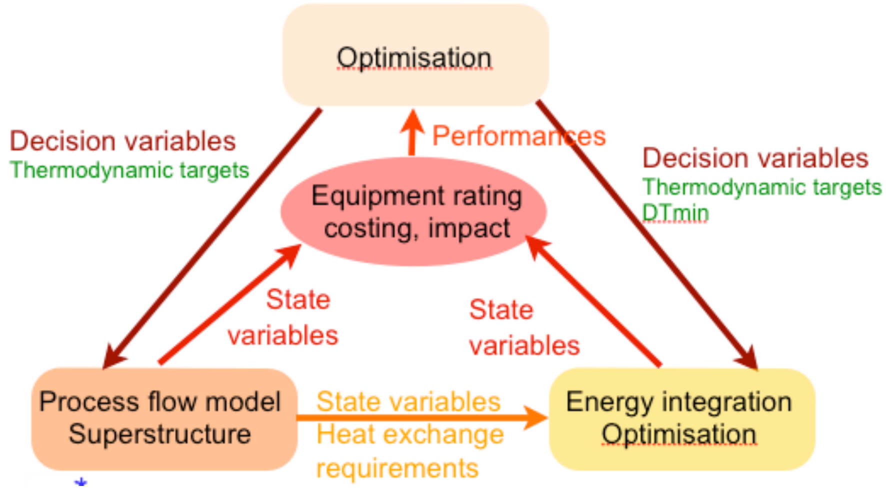
Access to solvers

- MILP/MINLP solvers
  - Mathematical Programming Language
    - GLPK (MILP-Open source)
    - AMPL (MILP and MINLP - Proprietary)
  - Solvers
    - LPSOLVE (Open Source)
    - Gurobi
    - CPLEX
    - BONMIN
    - Baron
    - NLPSOL
- Evolutionary algorithms
  - MOO (EPFL)
  - Dakota
- Parallelisation
  - MPI => grid computing

Computational platform - OSMOSE



OSMOSE : Computer Aided Platform

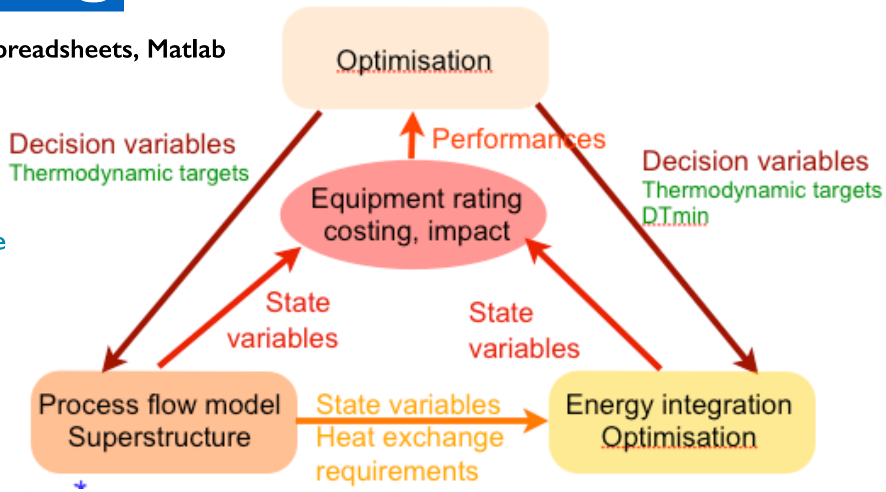


Data Structuring

GIS data base
- Industrial ecology
- Urban systems

GUI : Spreadsheets, Matlab

Technology models data base
- Energy conversion
- Sharing knowledge



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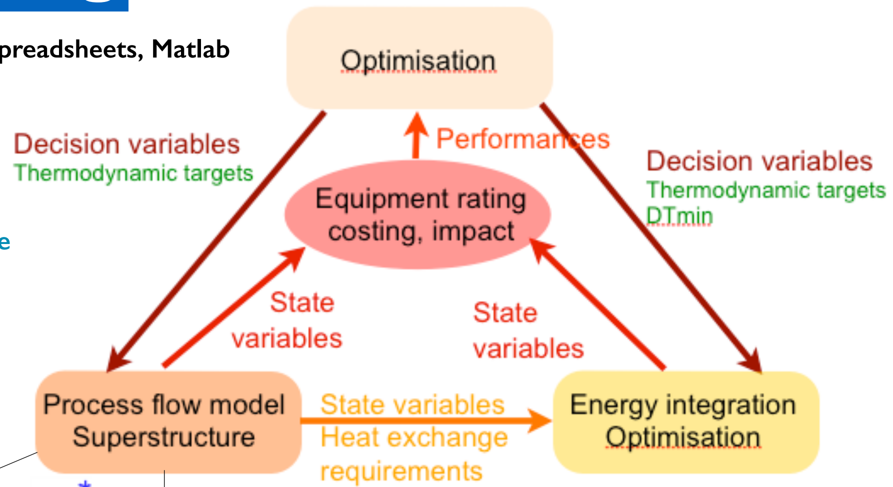

Flowsheeting tools
- •BELSIM-VALI
- •gPROMS
- •ASPEN plus
- •HYSYS
- •Matlab
- •Simulink
- •(CITYSIM)
- •MODELICA
- •Others possible
  - •CAPE-OPEN ?
  - •PROSIM
  - •UNISIM ?

Energy technology data base
- •Data/models interfaces
- •Simulation
- •Process integration interface
- •Costing/LCIA performances
- •Reporting/documentation
- •Certified dev procedure

Modeling tools integration

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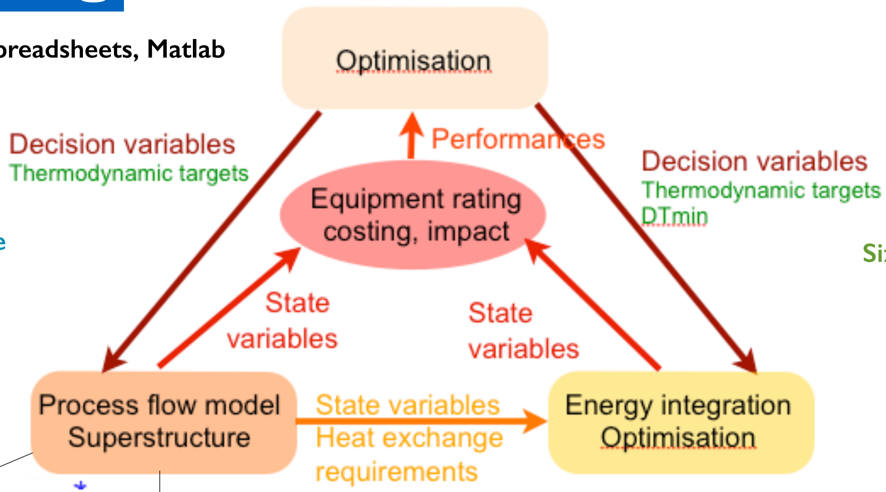

Sizing/costing data base
- LCIA database (ECOINVENT)

Optimal control models
- MILP/ AMPL or GLPK
- Multi-period problems

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MILP/MINLP models
- Heat/mass integration
- Sub systems analysis
- Superstructure
- HEN synthesis models

Process integration

Modeling tools integration

OSMOSE : Computer Aided Platform

Grid computing

Decision support

Multi-objective optimisation
- Evolutionary - Hybrid
- Problem decomposition
- Uncertainty

Data Structuring

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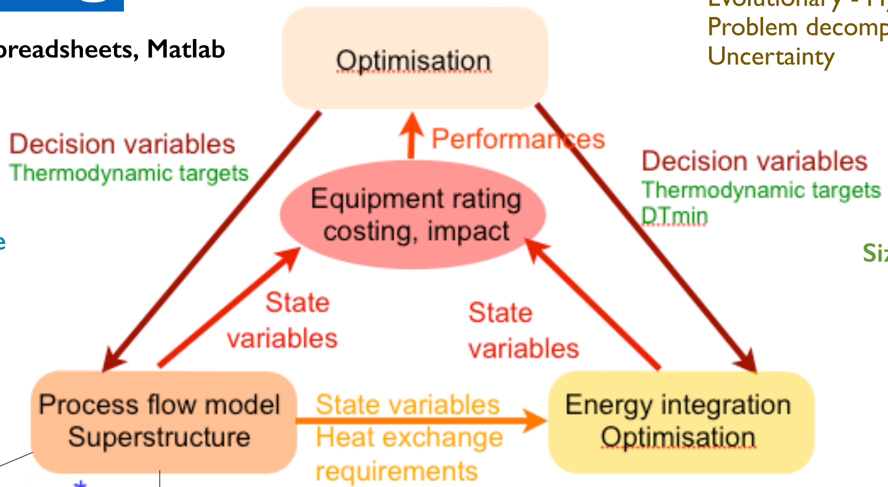

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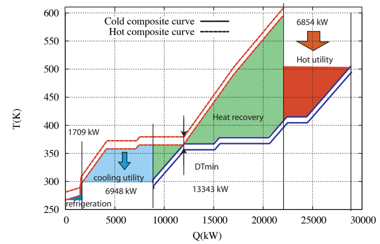
- •Simulation
- •Process integration interface
- •Costing/LCIA performances
- •Reporting/documentation
- •Certified dev procedure

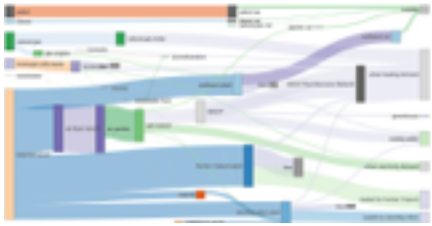
MILP/MINLP models
- Heat/mass integration
- Sub systems analysis
- Superstructure
- HEN synthesis models

Process integration

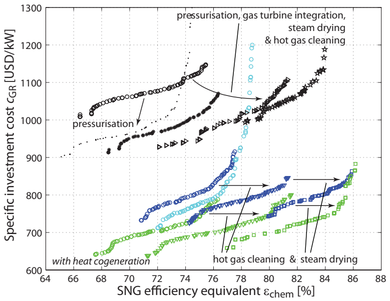
Modeling tools integration

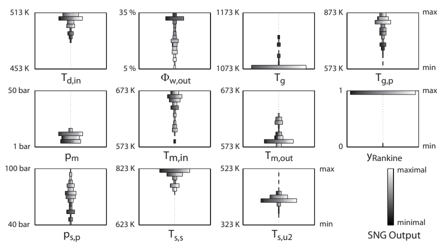
Results analysis

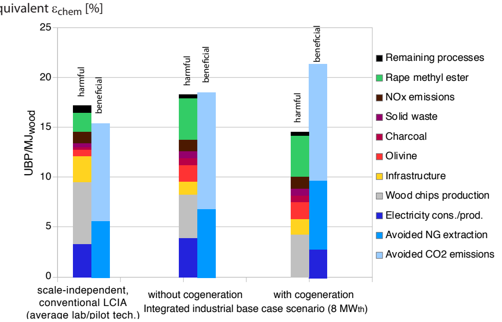




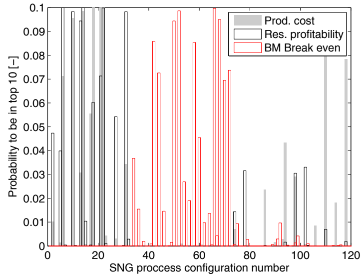
- Graphical representations
  - Composite curves
  - Sankey diagrams
- PDF reports
- Sensitivity analysis
- Pareto curves => data base of solutions
  - Decision variables values







- Uncertainty analysis => most probable optimal solutions



Case study

Context of the project

PF(E)^3 project:

Calculation **P**lat**F**orm for **E**nergy **E**fficiency and **E**nvironmental optimisation

- Started in January 2013, duration of 30 months
- Tool for design and decision making based on the notion of cost/benefit
- Use of OSMOSE platform from EPFL's IPESE group

EPFL, IFP Energies Nouvelles, IDEEL, EDF R&D, Armines CEP, …

Case study

Input data

A city of 100,000 habitants

Resource	Price	Units	Uncertainty
Biomass (wood)	*0.05*	*€/kWh*	*±30%*
Biomass import	*0.10*	*€/kWh*	*±30%*
Natural gas	*0.078*	*€/kWh*	*±30%*
Electricity (grid)	*0.20*	*€/kWh*	*±30%*
Oil	*1.05*	*€/kg*	*±40%*
Diesel	*1.80*	*€/kg*	*±40%*
Petrol	*1.88*	*€/kg*	*±40%*
DME	*0.65*	*€/lit*	*±50%*
FT diesel	*0.125*	*€/kWh*	*±50%*
MeOH	*0.323*	*€/lit*	*±50%*

Services	Value	Units
Mobility	*36.1*	*pkm/s*
Electricity	*22,000*	*kW*
Hot water	*24,210*	*kW*
Space heating	*117,623*	*kW*
Wastewater	*0.95*	*m3/s*
Municipal waste	*2.23*	*kg/s*
Municipal organic waste	*0.51*	*kg/s*

Industry	Size	Units
Sawmill	*100,000*	m^3 *wood*$_{in}$*/y*
Greenhouse	*12,000*	*tonnes tomatoes produced/y*
Laundry service	*20,000*	*tonnes dirty clothes washed/y*
DME plant	*50*	MW_{thBM}
FT plant	*100*	MW_{thBM}
MeOH plant	*50*	MW_{thBM}

Case study

Models

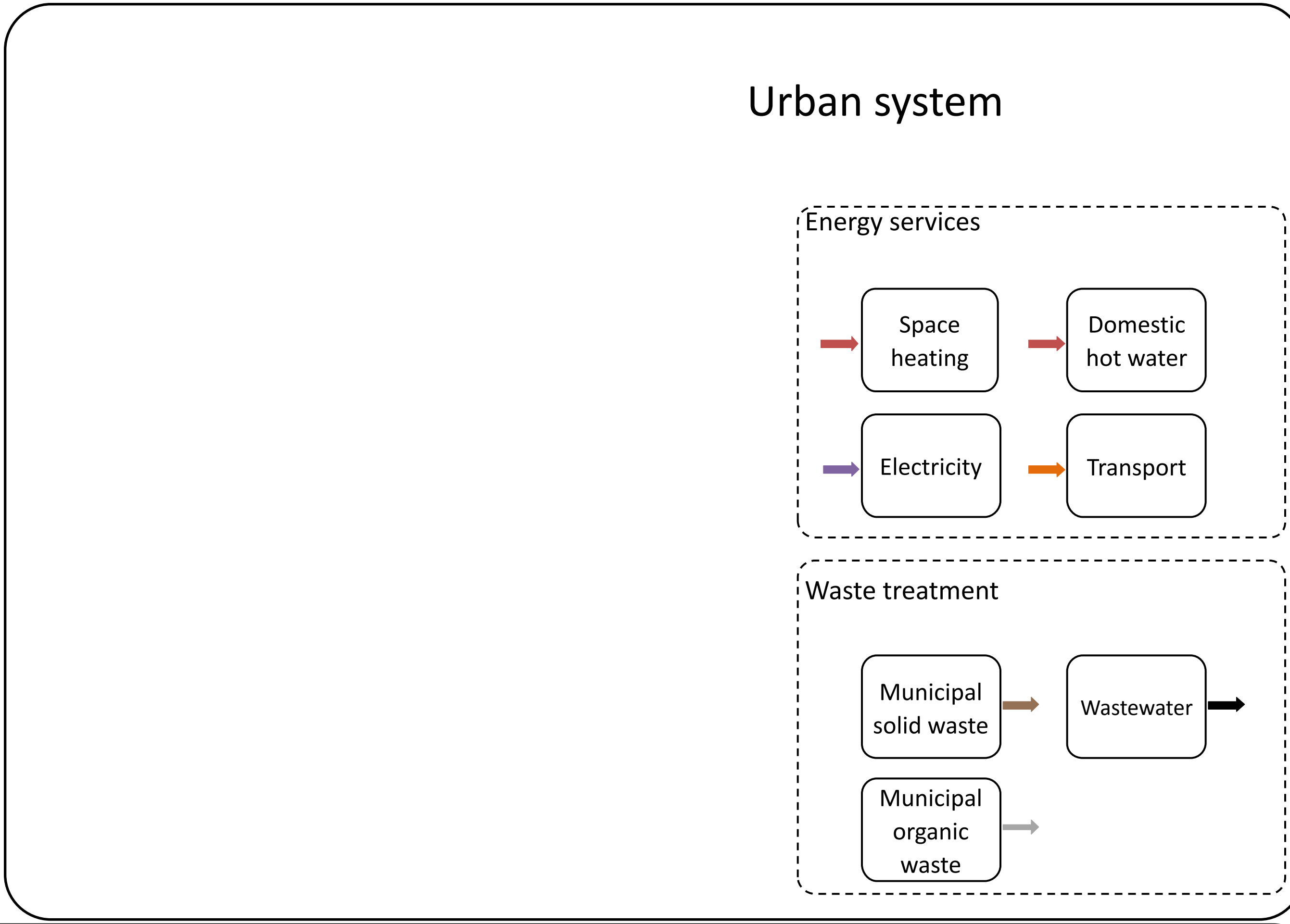
Case study

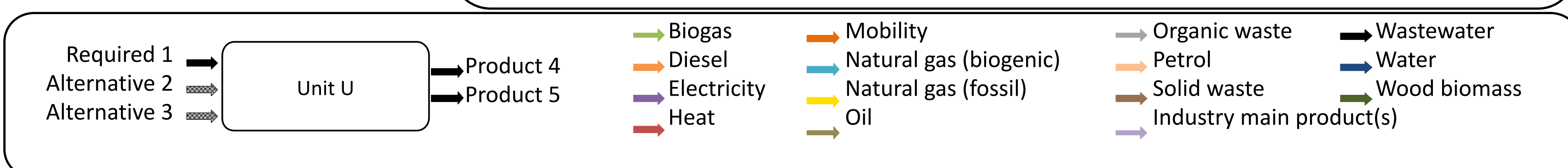
Models

Urban system

Case study

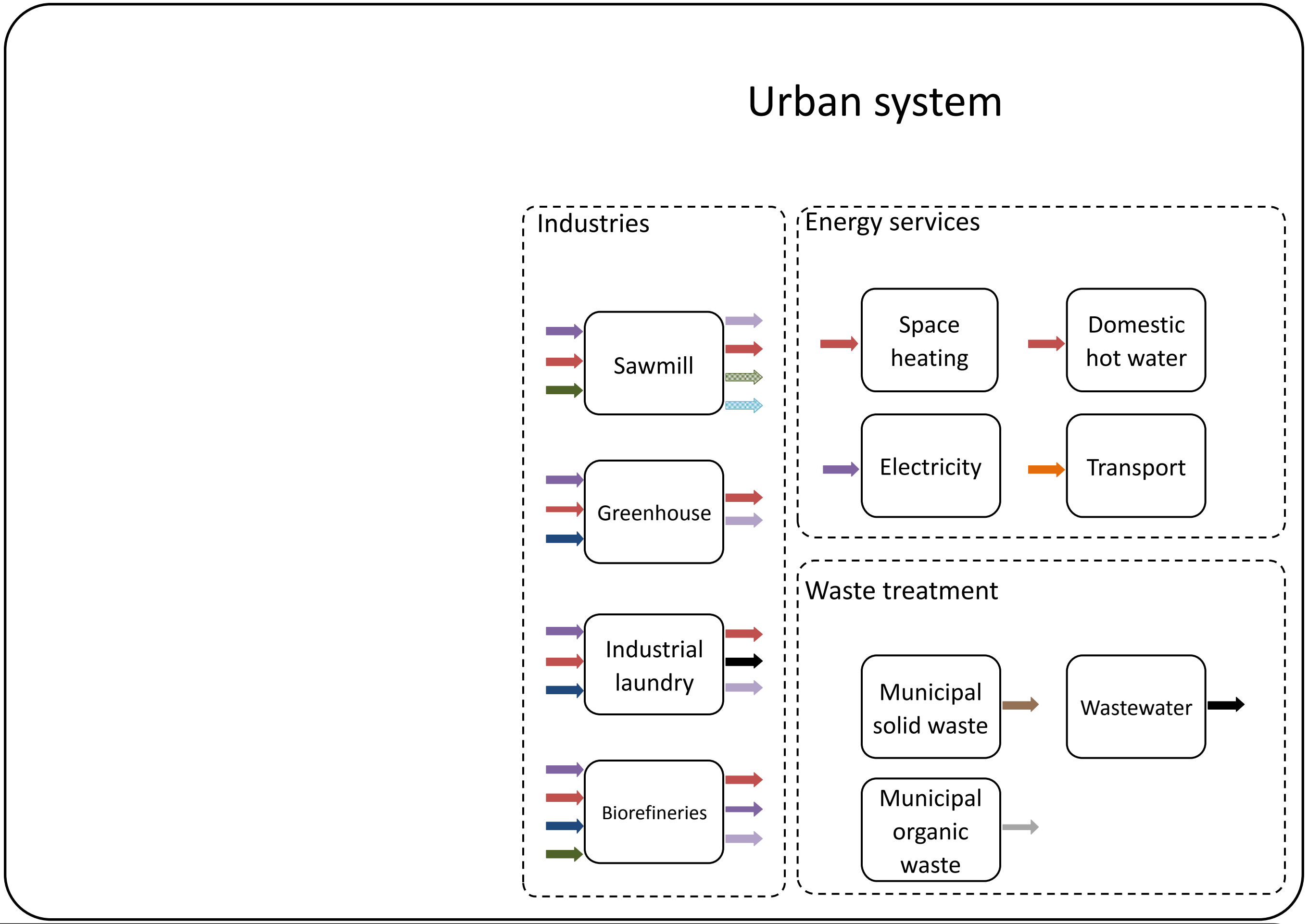
Models

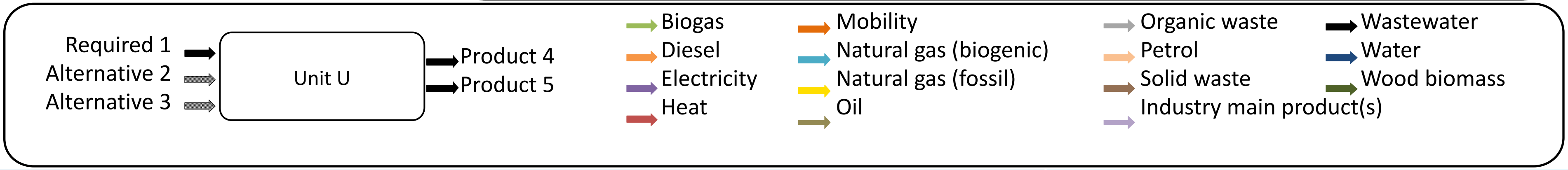




Case study

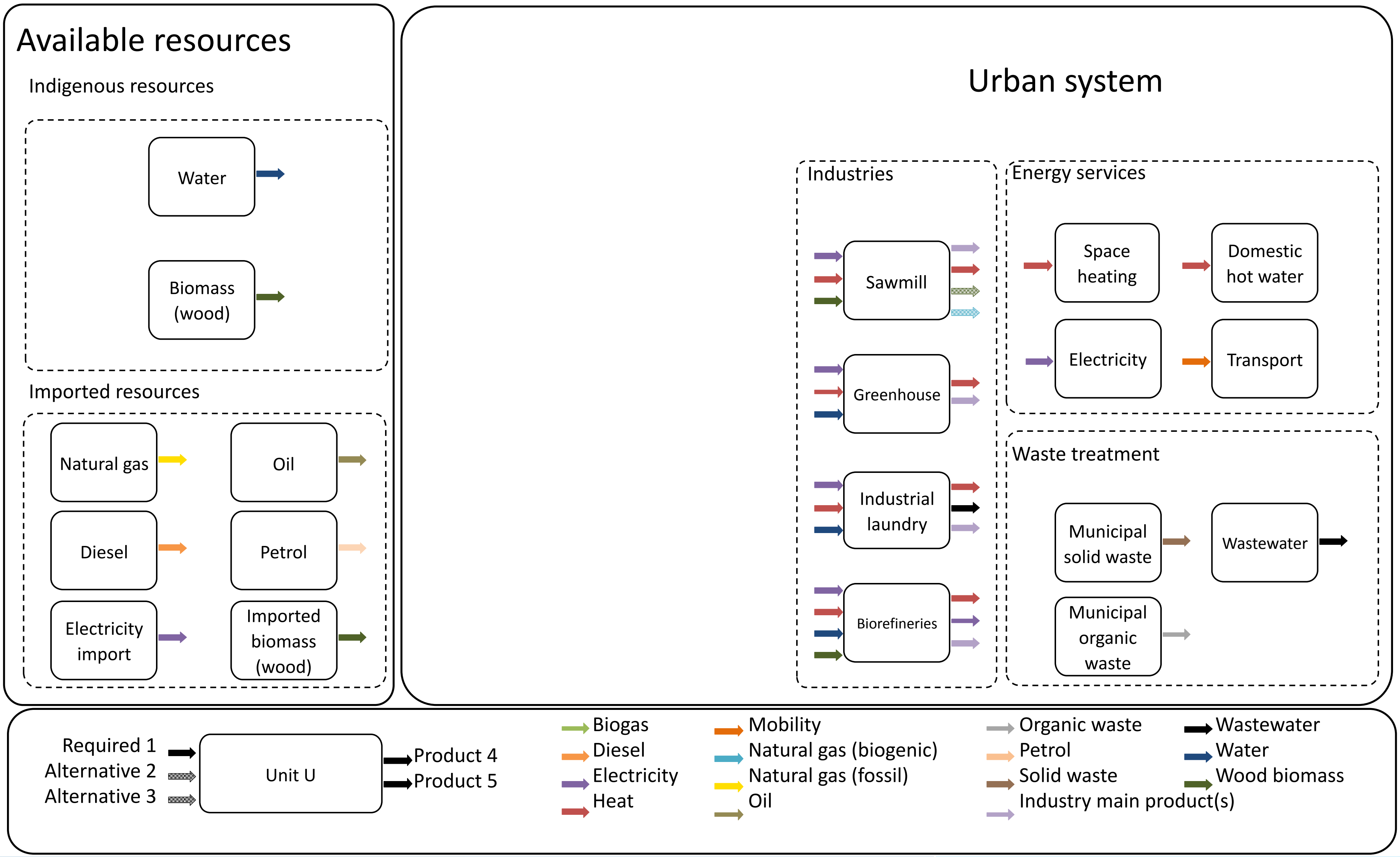
Models





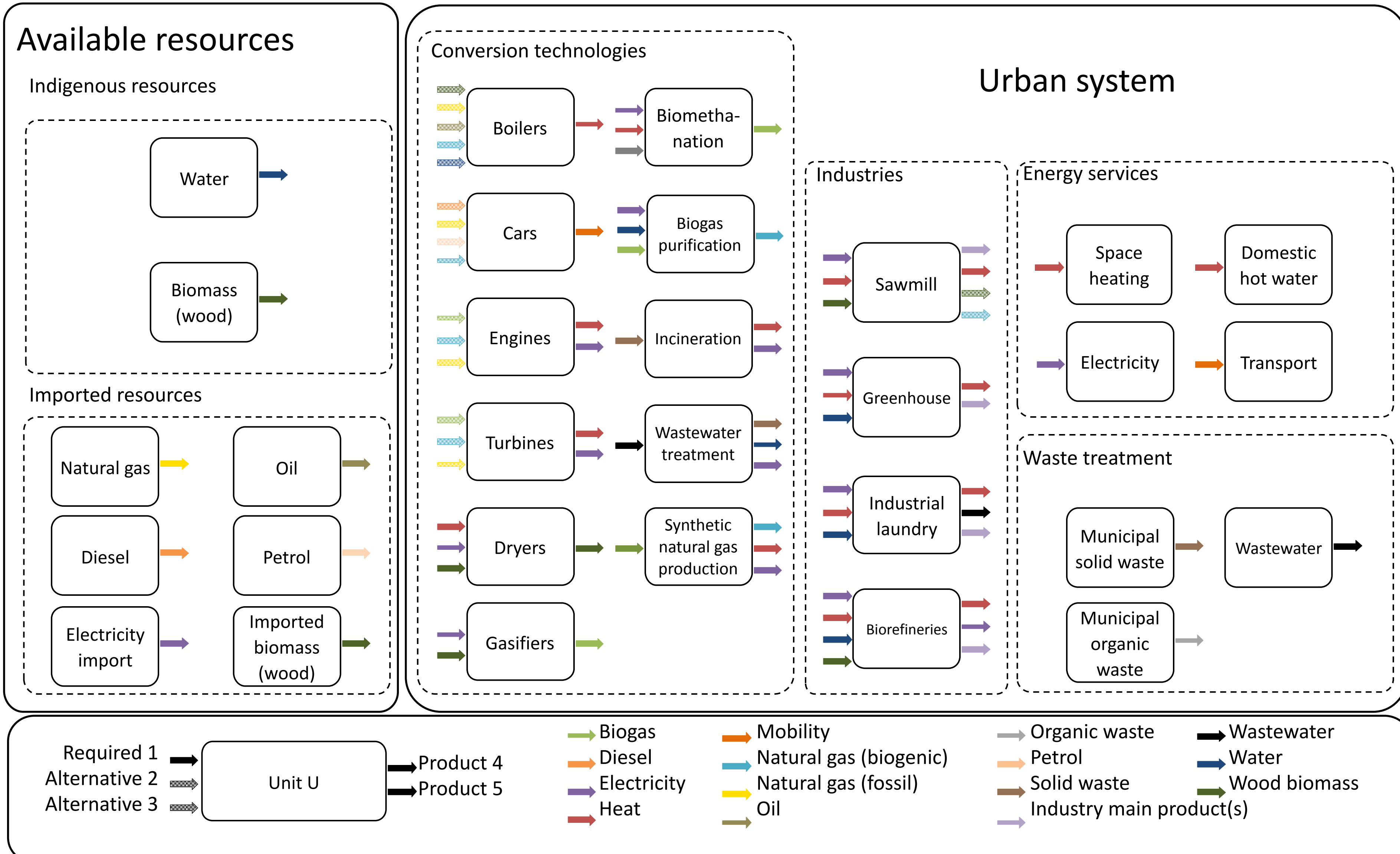
Case study

Models



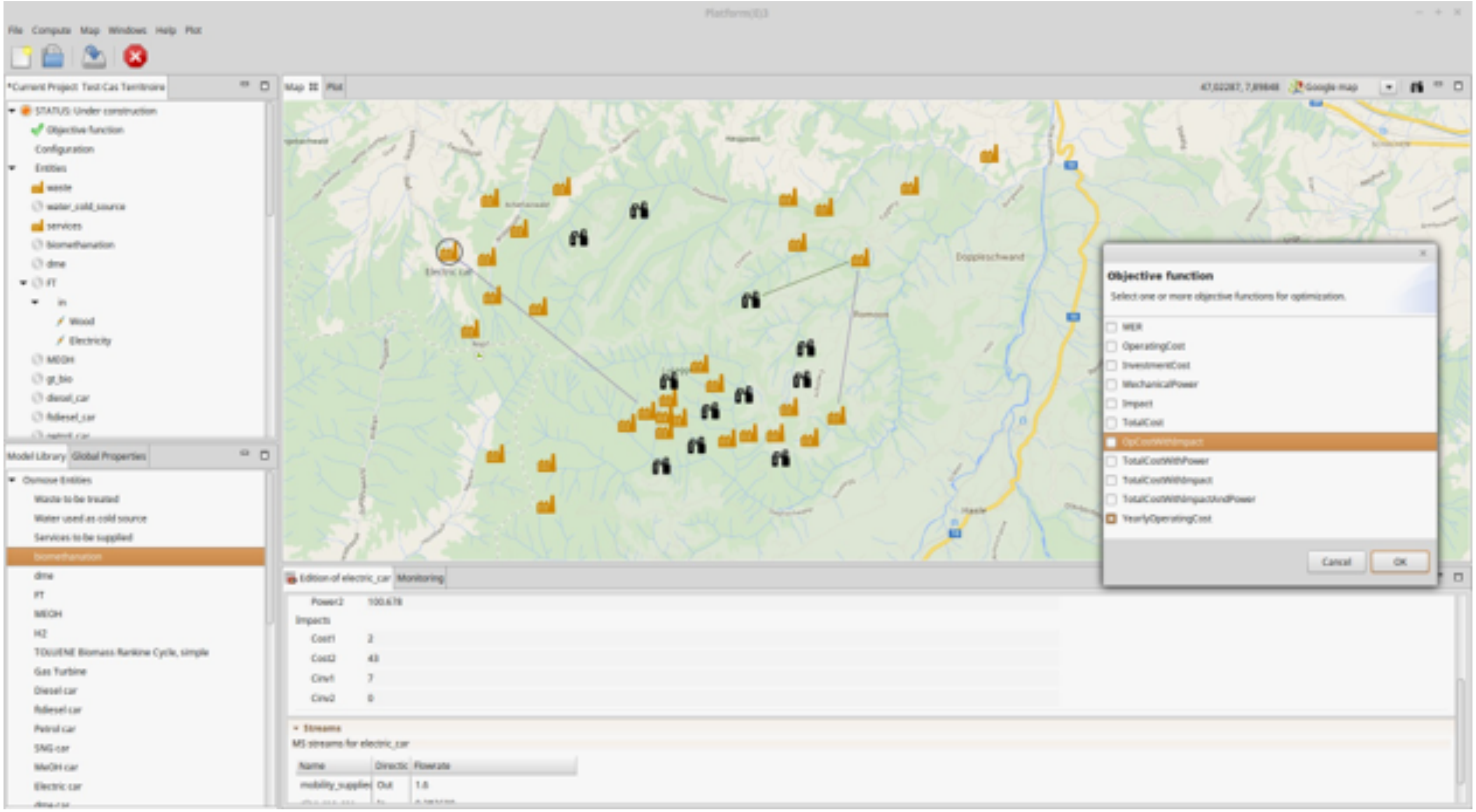
Case study

Models



Case study

User-interface



Case study

Assumptions

Business as usual (BAU)

- Space heating[1]
  - Heat recovery from MSWI
  - 57% fuel oil, 18% natural gas, 14% biomass (wood), 11% electricity
- Hot water
  - Assumed same as space heating
- Transport[2]
  - 24% diesel, 76% petrol
- Industries
  - Biorefineries self-sufficient
  - Others → heat from natural gas
- Electricity
  - From MSWI
  - From grid (UCTE)

Case study

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  - From MSWI
  - From grid (UCTE)

Optimisation constraints

- Space heating and hot water
  - Possible heat recovery from MSWI, WWTP, industries (refineries, laundry service), organic waste (OW) biogas
- Transport
  - 56% diesel / petrol
  - 44% non fossil fuel driven
- Industries
  - Heat recovery when possible
- Electricity
  - From MSWI, WWTP, OW biogas
  - Remainder from grid (UCTE)

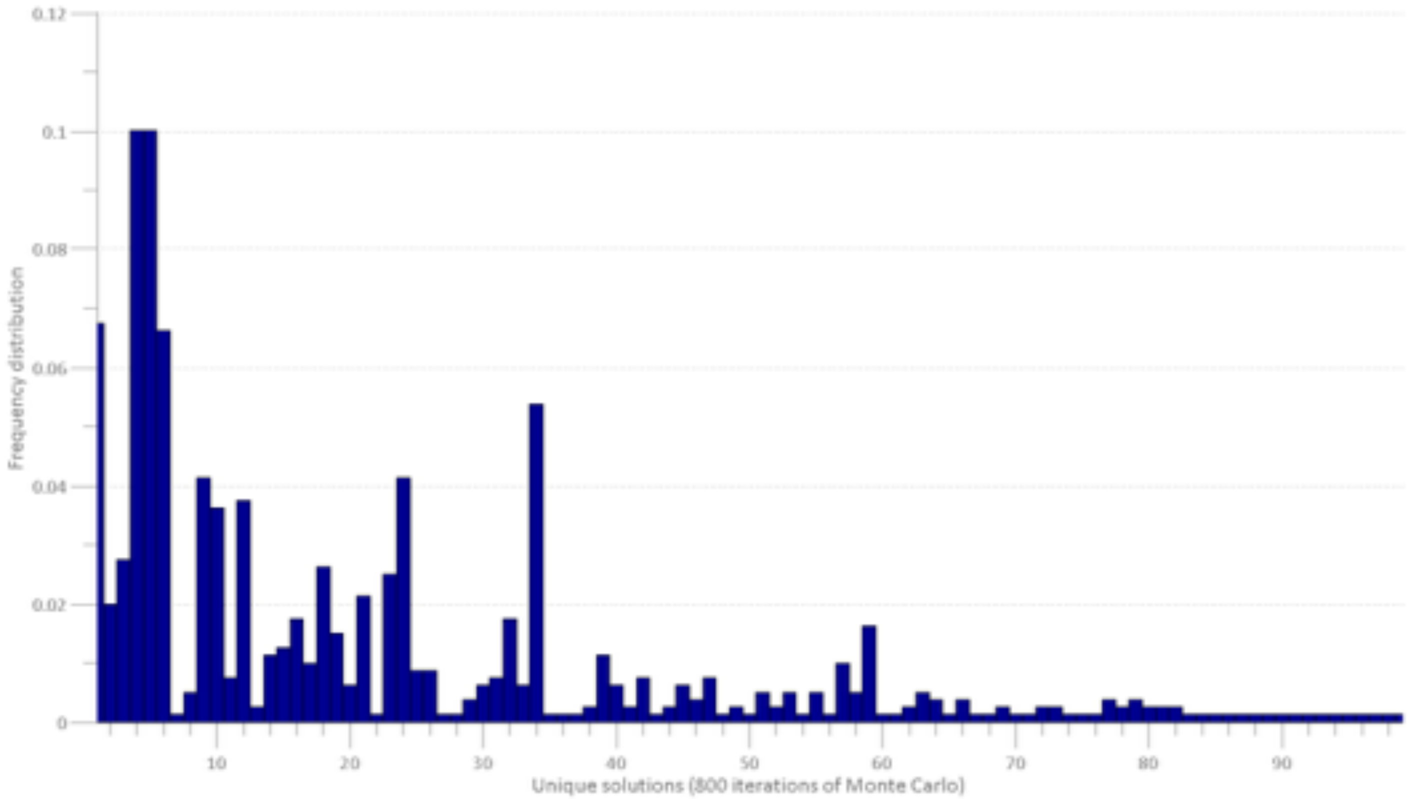
Case study

Result of optimization

Monte Carlo simulation

- Prices of resources are subjected to uncertainty
- Finding the most resilient solutions

Probability of being the best solution in 800 Monte Carlo simulations

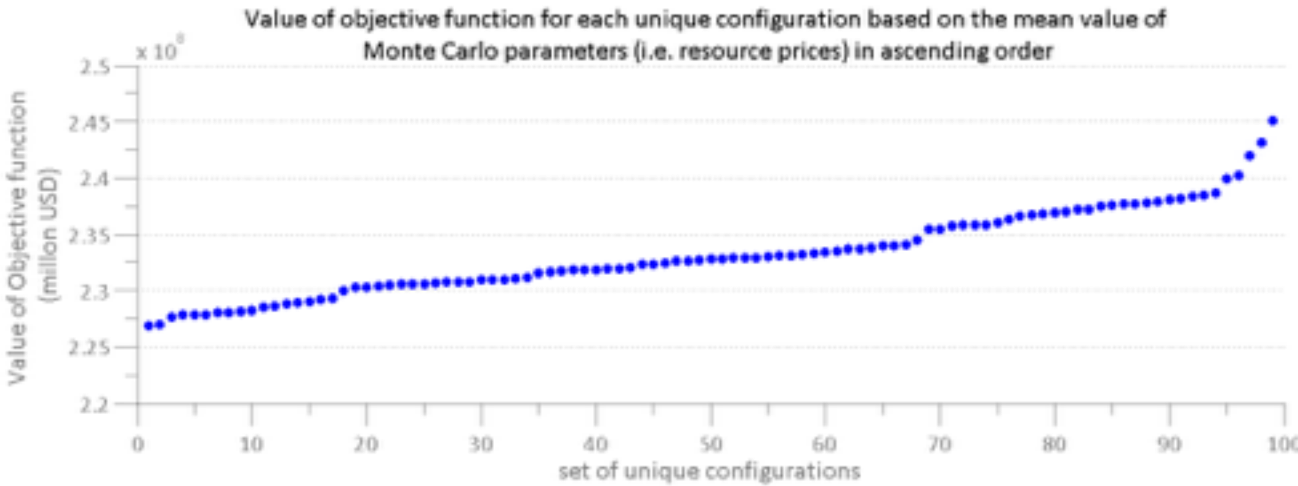


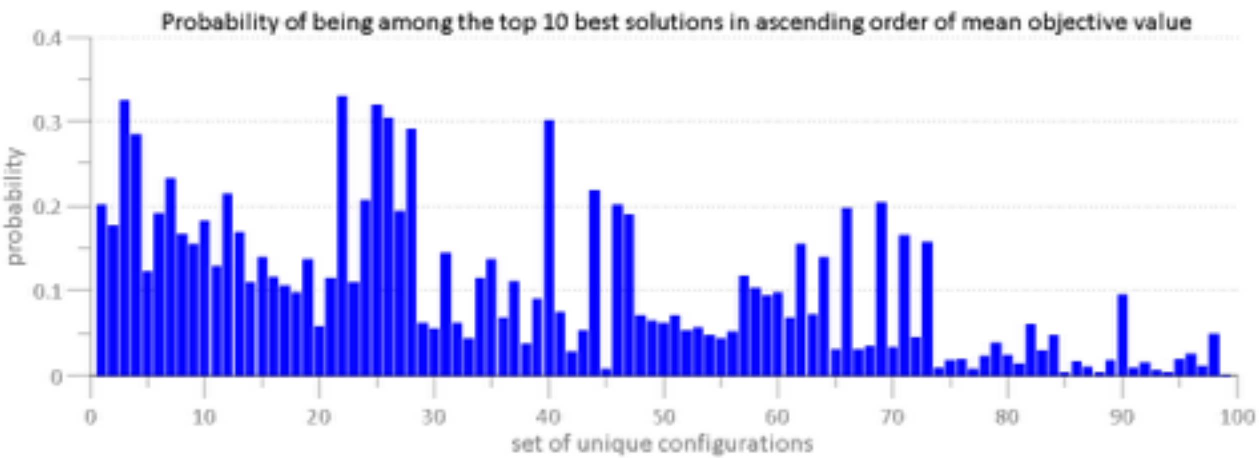
Case study

Result of optimization

Monte Carlo simulation

- Prices of resources are subjected to uncertainty
- Finding the probability of being among the top 10 best solutions



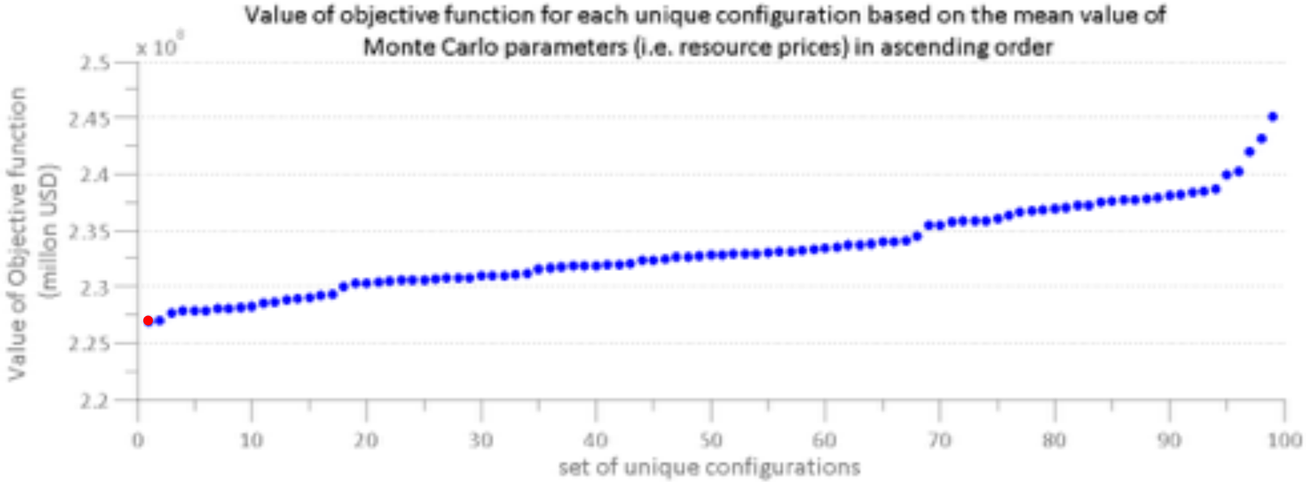


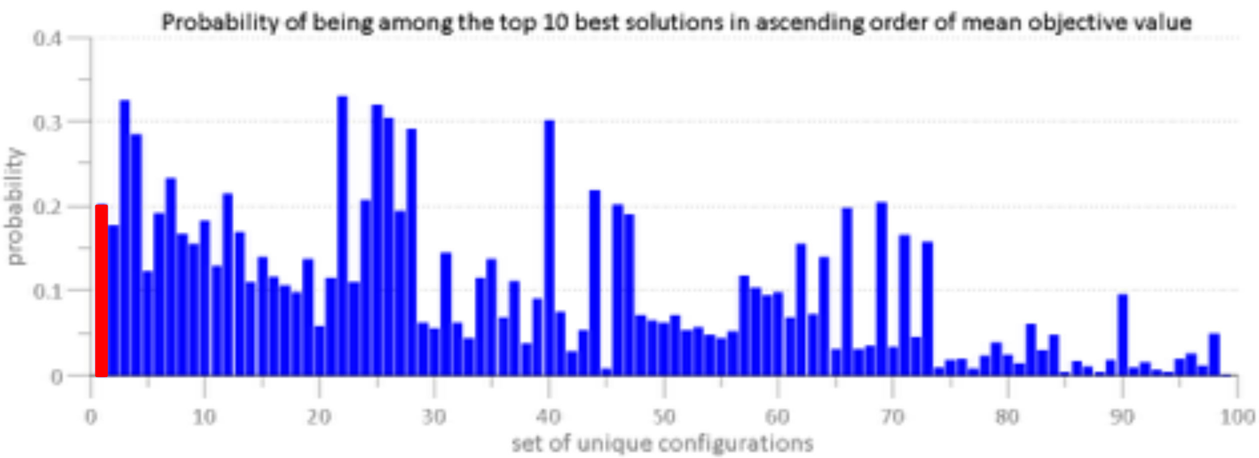
Case study

Result of optimization

Monte Carlo simulation

- Prices of resources are subjected to uncertainty
- Finding the probability of being among the top 10 best solutions



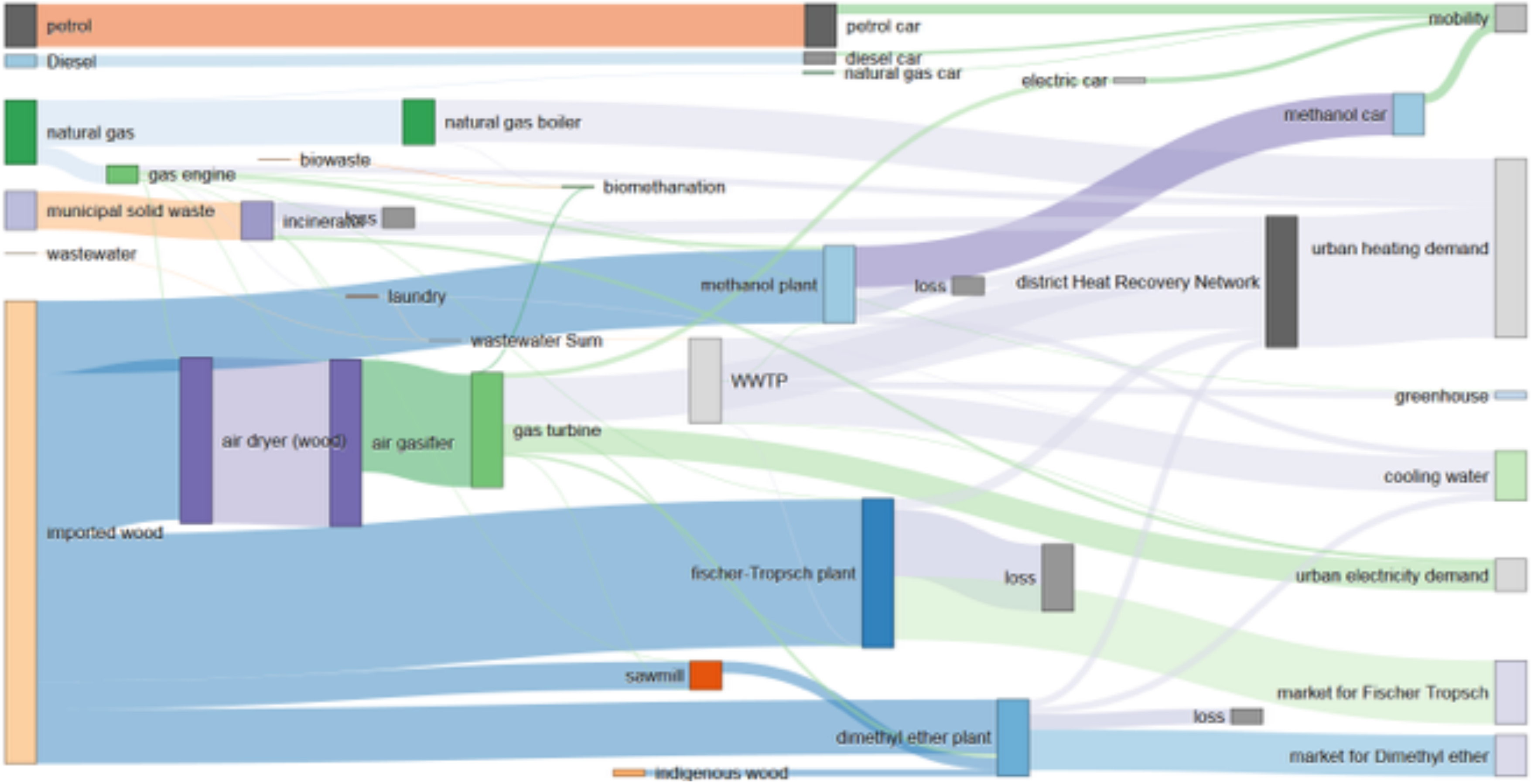


Case study

Result of optimization (one solution in the set)

Total environmental impacts = 492,000 tons of CO_2-eq/yr

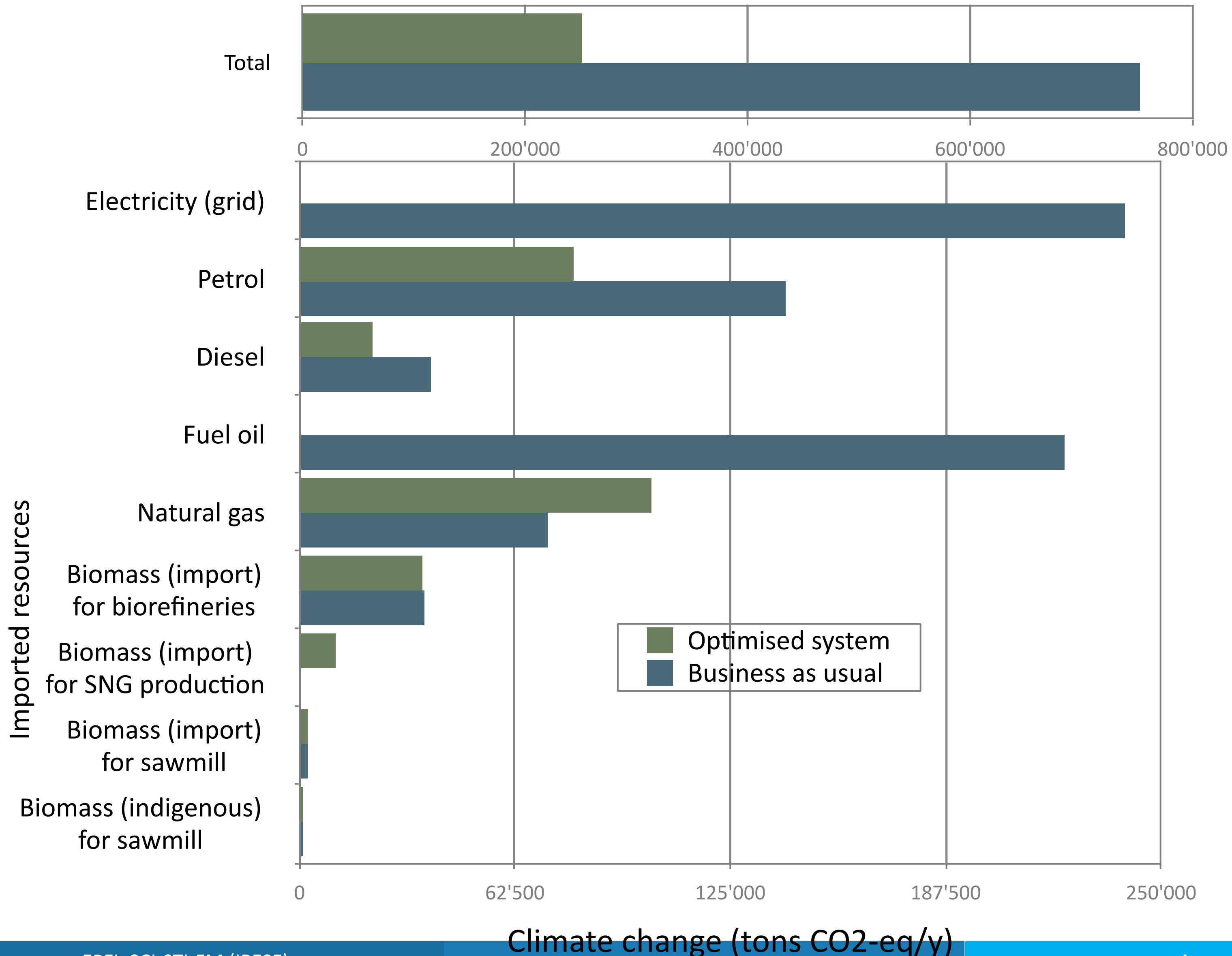
Total operating cost = 226.8 million CHF/yr



The thicknesses represent the size of the connection in "**kW**" (except for connections to mobility which are scaled up to be visible)
Each colour represents one type of connection, e.g. electricity, heat, natural gas, wood, mobility, …

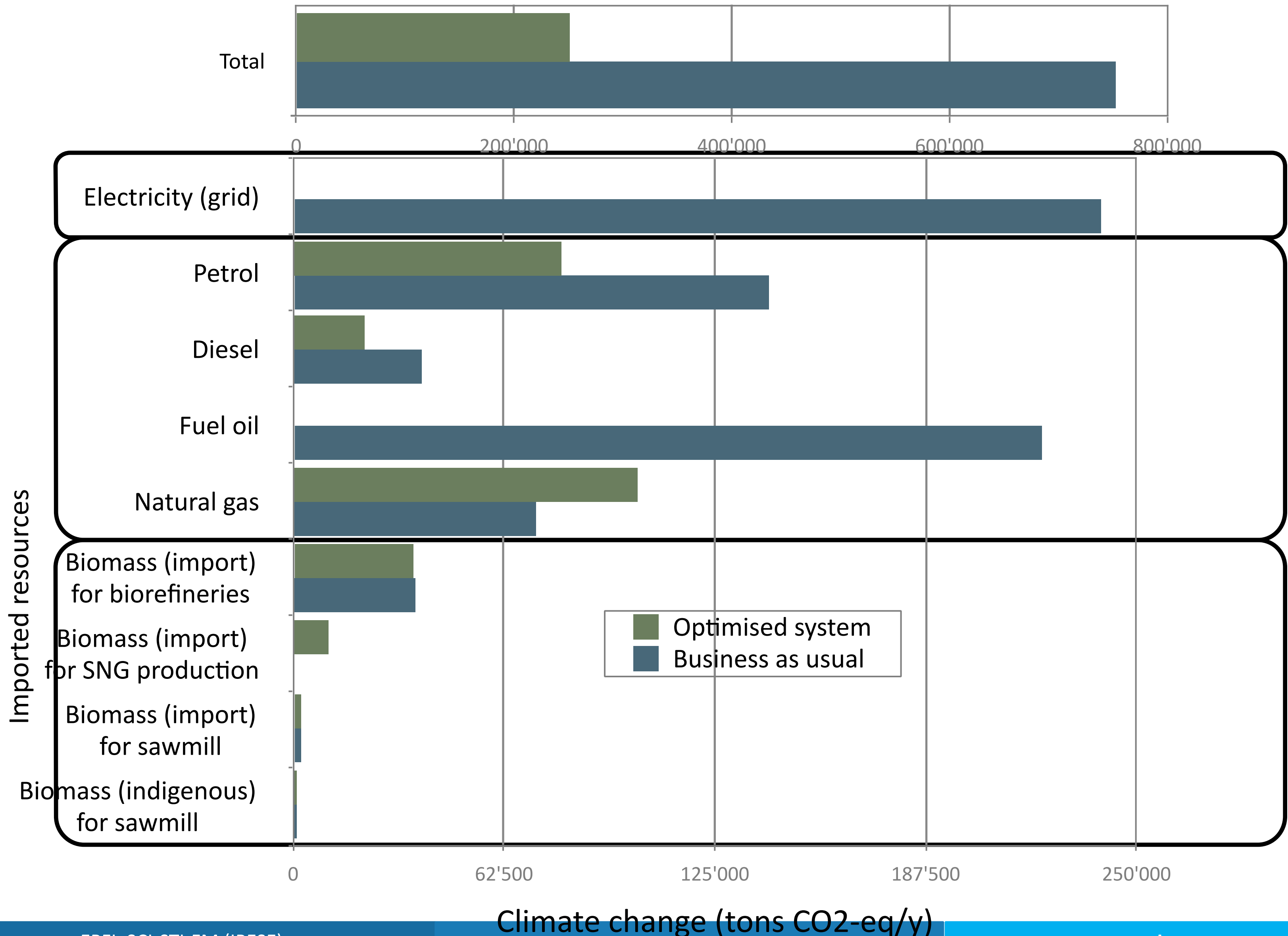
Case study

Climate change (tons CO_{2-eq}/yr)



Case study

Climate change (tons CO_{2-eq}/yr)



Conclusions and future work

- Data management platform
  - Data bases
    - Technology Models => Ontology
    - Connectivity => Ontology
    - Geographical information system => SQL
    - Life Cycle Inventory => SQL
    - Costing
- Tools integration and handlers
  - Flowsheeting tools
  - Routing algorithms
  - Data analysis and processing
    - Clustering
    - Statistical analysis
  - MILP problem formulation
  - Problem decomposition & methods
  - MILP/MINLP solvers

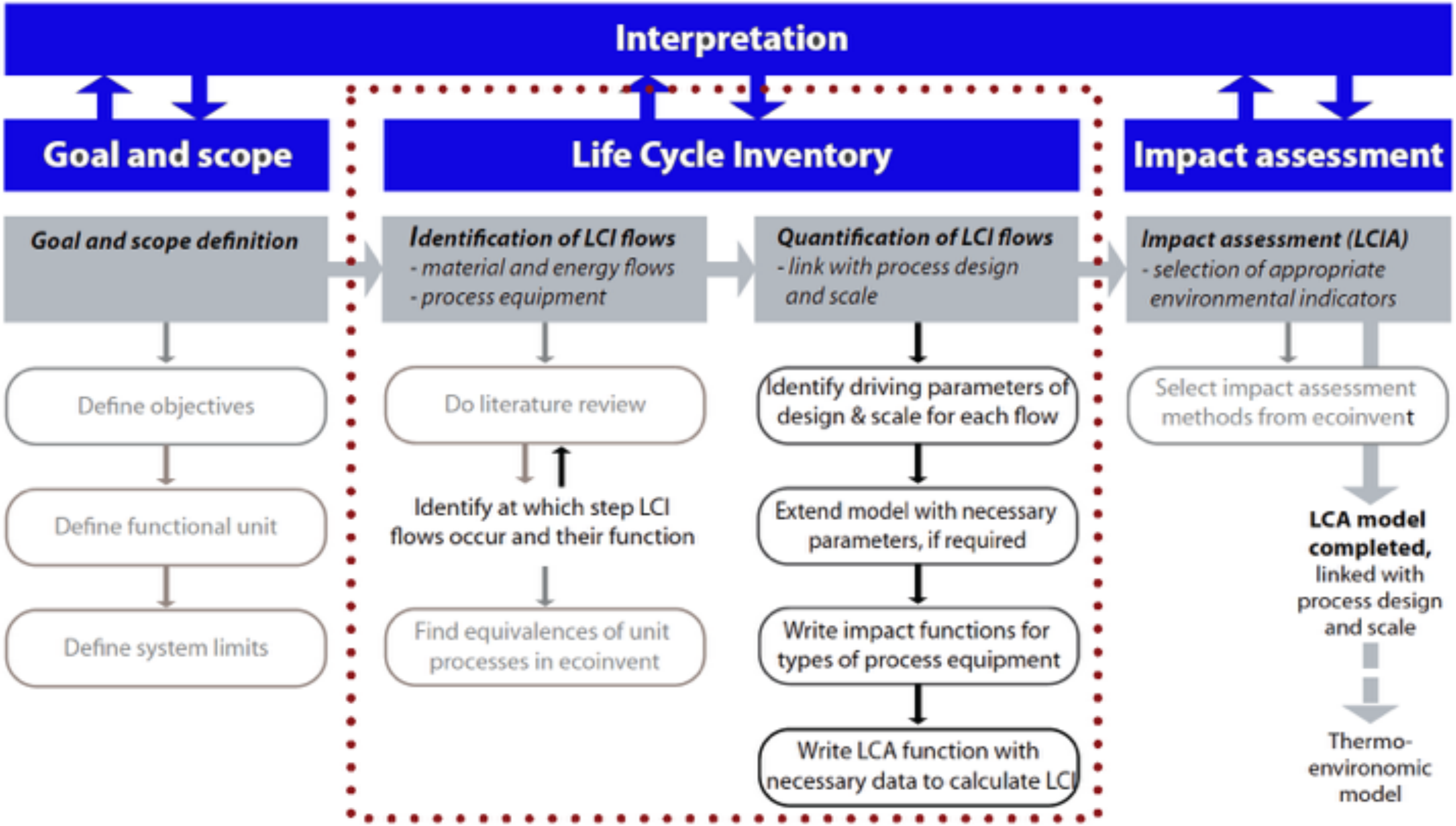
Conclusions

- Workflow organisation => list of tasks
  - Aggregation/disaggregation
  - Super-structure definition & models
  - Optimisation problems
    - Multi-objective
    - MI(N)LP
  - Parallel computing
  - Decision support & uncertainty
- Applications
  - Process design
  - Process integration & HEN design
  - Site scale integration
  - Industrial Symbiosis development
  - Urban Energy Systems development
  - Industrial ecology
  - Region-City scale development
  - Autonomous systems (Ships, cars)

Thank you for your attention!

Appendices

A1. Life Cycle Impact Assessment (LCIA) in Osmose-Lua



Source: Gerber, L., Gassner, M., and Maréchal, F. (2011). *Systematic integration of LCA in process systems design: Application to combined fuel and electricity production from lignocellulosic biomass*. Computers & Chemical Engineering *35*, 1265–1280.