CI-NERGY Project – Deliverable 10

High level decision support prototype tool

Lead Beneficiary : AIT EPFL

Table of Contents

1. Introduction

The CI-NERGY Marie Curie Initial Training Network (ITN) aims to train young scientists to develop urban decision making and operational optimisation software tools to minimise non-renewable energy use in cities. As such, one of the expected outcomes of the project is a decision making tool to help solve problems in urban energy system planning, design and operation. This tool should be based on the concepts and methods developed by the CI-NERGY ITN, which brings together a multi-disciplinary and cross-sectorial team of researchers, combining the academic excellence of renowned research institutes with the practical experience of companies and public authorities.

To verify the achievement of this task, milestones 8 and 9 were set. The former is a finalised high level decision making platform prototype, and the latter a finalised detailed level simulation platform prototype. The deadline of these milestones is M36, corresponding to end of September 2016. The goal of the present deliverable (D11) is to report on milestone 8 specifically.

Regarding the achievement of milestone 8, the prototype decision making platform[1] is not yet available at this stage per se. One of the principal explanations for this is the fact that such a platform relies strongly upon the development of individual tools and methods by the different ESRs before any integration can take place. As these tools are being developed in the context of PhD theses, there is an initial time required to define the research goals of each researcher, before the development of any tool or method can start. Moreover, the recruitment of some ESRs and ERs was delayed by several months compared to the initial planning.

Nevertheless, steps have been taken throughout the project to go in this direction and achieve this goal. Currently, a model-based methodology to support early stage local urban and energy planning has been developed and applied to a case study site, and is presented in this deliverable.

The deliverable consists of 4 parts:

- Firstly, the initial **vision** of what the CI-NERGY framework should be is introduced. It sets out the goals towards which we aim.
- Secondly, the current status of the model-based **methodology** for early stage urban and energy planning is described.
- Thirdly, the results of the methodology applied to a **demo case study** are presented.
- Fourthly, the **remaining steps** to achieve the goal set out in the vision are revealed.

2. Vision

Thriving to bring together the cross-sectorial expertise of the different partners of the project, the initial vision that we had of the integrated framework for decision support in urban energy planning can be summarised by the schema presented in Figure 1. In fact, this incorporates both the detailed level simulation platform (object of milestone 9) and the high level decision making platform (object of milestone 8). It stems from interviews carried out by ER2 which took place between M12 and M18 of the project in order to have a better understanding of the research work and envisioned models of each ESR, and their potential contribution to the CI-NERGY tool.

[1] Which we will also call the "CI-NERGY platform" or "CI-NERGY tool" throughout this document.

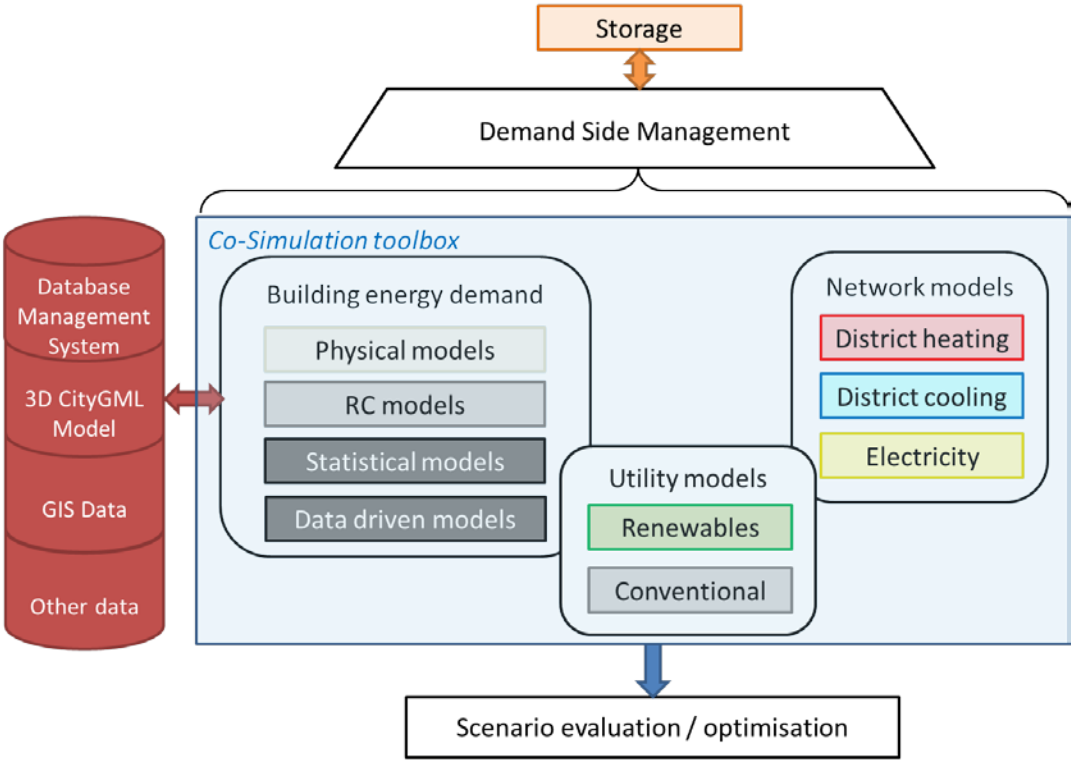

Figure 1 - Schema of envisioned CI-NERGY framework

In the co-simulation toolbox (milestone 9), several simulation models are combined using the FMI co-simulation standard. This includes simulation of network models (district heating/cooling and electricity grid), energy demand models of buildings and utility models. The co-simulation platform is coupled to a spatial database (including a 3D CityGML model of the city) which stores all the data required for the simulation and decision support platforms in a systematic way, reproducible for any city if sufficient data is available.

The co-simulation framework can be used to test different scenarios, such as building refurbishment or integration of renewable energy sources on the thermal and electricity networks. Moreover, different demand side management strategies including short or long term storage can be tested.

The co-simulation toolbox is then combined with a high level optimisation framework (milestone 8). Several options are foreseen to link simulation and optimisation:

- One option is to encapsulate the co-simulation toolbox in a master multi-objective optimisation using a genetic algorithm, in which certain chosen parameters of the simulation models can become decision variables of the master optimisation.
- Another option is to generate a simplified model (e.g. MILP model) of the system for the optimisation, which is carried out in a first step. The most promising results of the optimisation are then evaluated in more detail using the co-simulation toolbox.
- The last option consists in using separate simulation models for different parts of the system to calculate parameters required for the optimisation. For example, building demand profiles, which is an input to the optimisation, can be pre-calculated using simulation.

The optimisation platform which is presented in the next section is mostly compatible with the last two options, but could also be additionally combined with the first option, as presented in 5.3. However, the coupling with simulation or co-simulation has not yet been carried out.

3. Current status

The methodology which has been developed is the fruit of a close collaboration between ESR1 in EIFER and ESR4 in EPFL. It was enabled thanks to the secondment plans of the respective ESRs which allowed them to work together in the same location for several months. They presented their methodology in [1], and following is a summary of what is contained in the publication.

The goal was to use an optimisation model approach in order to bridge the gap between urban planning, historically guided mainly by socio-economic values, and energy planning, which is too often considered in a second step, thus leading to bad energy system designs. More specifically, the method uses a Mixed Integer Linear Programming (MILP) model to identify optimal energy systems, and understand how they interact with the urban layout (distribution and size of buildings) at a district level. It was developed in the context of the planning framework of the Swiss canton of Geneva, as one of the case study cities of the project, but the method can be extended and generalised to other cities.

The workflow of the methodology is represented in Figure 2. Once a clear question has been identified, which can be for example "how to achieve a sustainable energy supply of a new urban district at the lowest possible cost?", two main steps are carried out in order to try to answer it:

1. The planning framework is synthesized through the definition of clear quantifiable goals and constraints in terms of urban planning and energy considerations. This is achieved by a thorough review of relevant legal and planning documents which apply to the local case study. Discussions with local planners and stakeholders are also very important at this stage. This part was carried out by ESR1.
2. The information provided from the previous step is translated into an MILP optimisation model. This was done by ESR4. The objective function of the optimisation is chosen based on one of the formulated goals, and other goals can be set as constraints of the optimisation problem. Once the problem is formulated, the optimisation is performed and the results giving the urban layout and energy supply strategy are analysed.

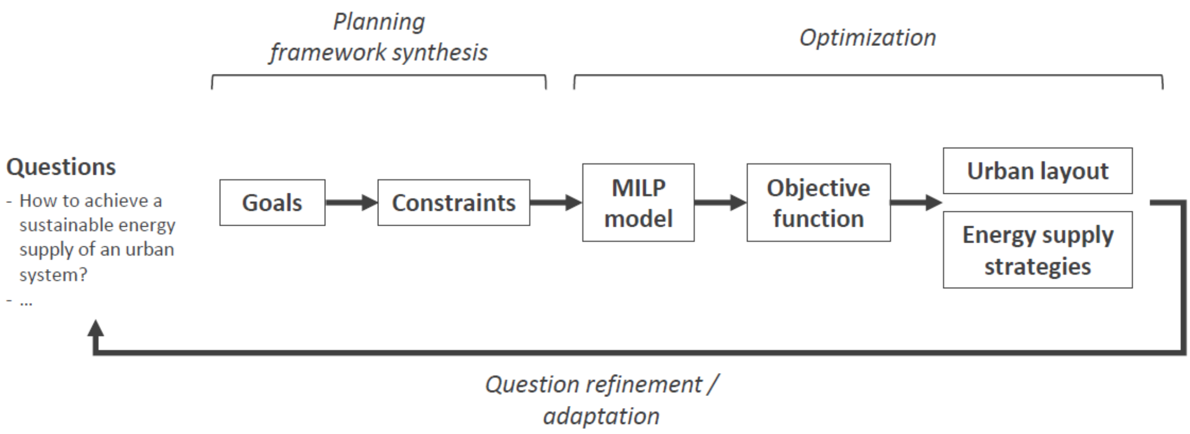

Figure 2 - Workflow of methodology [1]

Once results are obtained, it can be fed back to the questions in order to refine and adapt them. In turn, this can lead to the definition of new goals and constraints, as well as the formulation of a new optimisation model.

3.1 Planning framework synthesis

Urban planning relies on the use of multiple interacting instruments which span temporally across different stages, and vertically across different administrative levels. In the case of Geneva, the instruments taken into account and their position with respect to these scales are depicted in Figure 3. Other documents such as norms, cantonal laws and ordonnances were reviewed. In addition to that, several meetings with representatives of the Energy Office of the canton of Geneva, also partners of the project, took place to help understand and refine the goals and constraints. The main urban constraints which were considered include density, building heights and minimum distances between buildings. Regarding energy, constraints of interest included general efficiency and renewable energy supply. These were translated into the optimisation model.

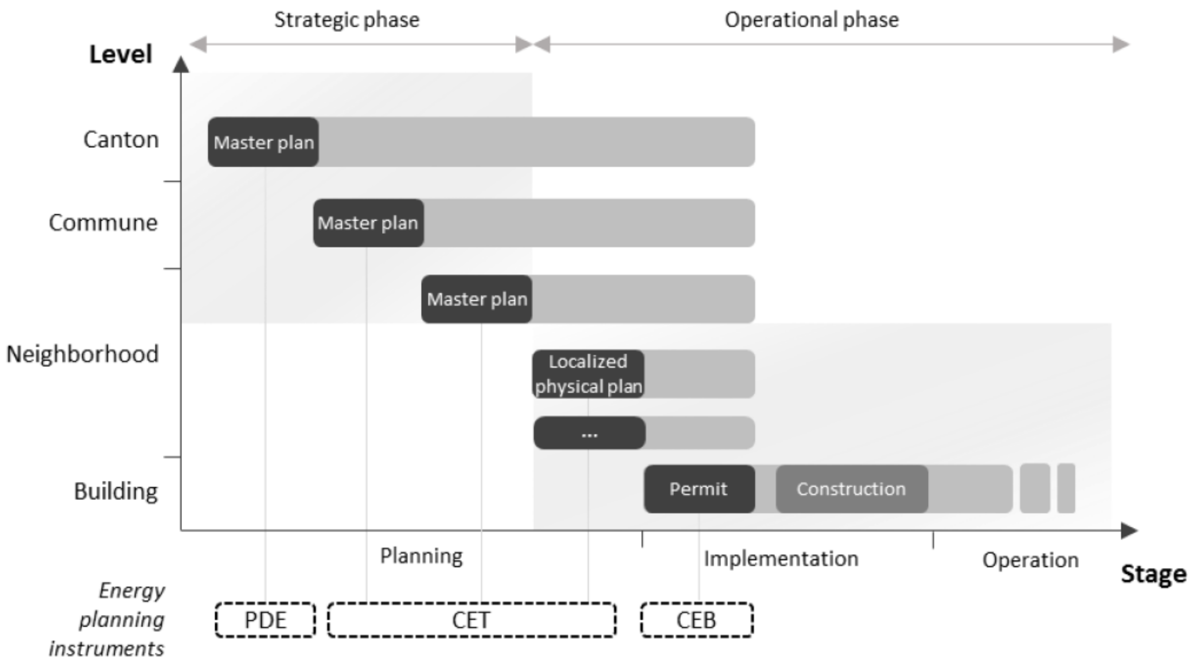

Figure 3 - Main planning phases and instruments in the Geneva context [1]

Although the procedure can be generalised, the actual review of legal and planning documents to extract useful information cannot be realistically performed automatically by a computer (at least not within the scope of this project as the issue is more to do with artificial intelligence), and therefore requires human intervention. Indeed, the format of the documents are not homogeneous and the information to seek depends on the question which is asked as well as the goal that needs to be achieved. To some extent however, it is expected that insights gained from the subsequent optimization stage will also provide more general guidelines supporting the integration of energy issues in urban planning.

3.2 Optimisation

The second part of the workflow consists in using optimisation to provide answers to identified questions. To this end, an existing computational framework for modelling and optimisation of energy systems (called OSMOSE) was extended to meet urban specific requirements, such as taking into account the urban planning constraints mentioned above and interfacing with a Geographic Information System (GIS).

3.2.1 OSMOSE Framework

OSMOSE has been developed by the IPESE group of EPFL. It is a computational platform - acting as a bridge and data exchanger among different software and tools (databases, simulation, optimisation solvers, data visualisation and reporting) - to help decision making for the design and operation of various systems (energy, supply chains, industrial processes etc.). A research tool in essence, it also aims at capitalizing the knowledge acquired and methods developed by the research group. It is currently coupled to a limited number of software/tools, but undergoing a continuous development process with the constant integration of new tools and methods.

The workflow of OSMOSE is shown in Figure 4. A frontend, defining the main project parameters, is launched. This loads a set of Energy Technology (ET) models which structure data in a systematic way, taking information provided in data files or databases. The models can be simulated by external software in the pre-compute to calculate model parameters. The models are then parsed into MILP models which are provided as input to an external optimisation solver. The results of this solver are recovered and further calculations can be carried out in the post-compute, before results are saved and displayed. A multi-objective optimisation can also be carried out on top of that workflow (see section 5.3).

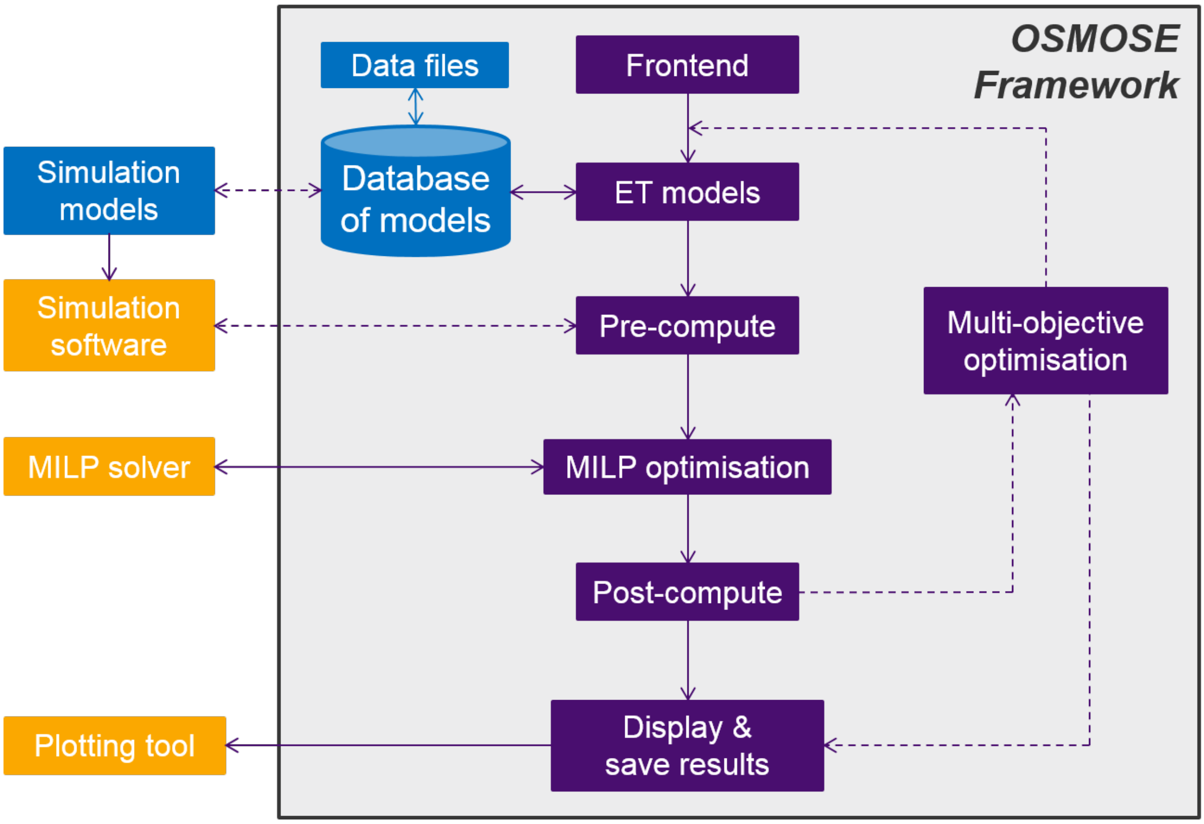

Figure 4 – Workflow of OSMOSE

3.2.2 Adaptation to urban systems

As mentioned above, the general OSMOSE framework has been adapted to study urban systems. Firstly, a specific MILP optimisation model has been implemented. Secondly, an object oriented model of urban energy systems was developed which serves to instantiate MILP models for buildings, utilities and networks.

The core of the framework consists in the MILP optimisation model. It consists in a set of linearized equations describing the behaviour of different energy utilities, networks and buildings, and it allows to identify the best possible combination of technologies to fulfil the energy demand (heat, electricity) with respect to a given objective (cost, environmental impact). The additions made to this model include:

- Additional equations to represent urban considerations (building footprint) and respect the urban planning constraints (minimum density, maximum building height for different building usage)
- Inclusion of additional utilities such as solar PV
- A simplified model for heating networks and pipe length estimation
- Energy target constraints to respect ("2000 W society" target of covering 75% of the energy supply with renewable energy sources)

One of the challenges of urban energy systems modelling lies in its high complexity, in particular the high number of elements which composes them (e.g. number of buildings). Hence, writing a model by hand would be extremely time-consuming. To cope with this, a generic object-oriented model of each urban energy system component type (buildings, utilities and networks) was developed and a procedure to automatically instantiate the MILP model of an element from information provided in a database was implemented. The procedure is represented in Figure 5 and was integrated in the OSMOSE framework.

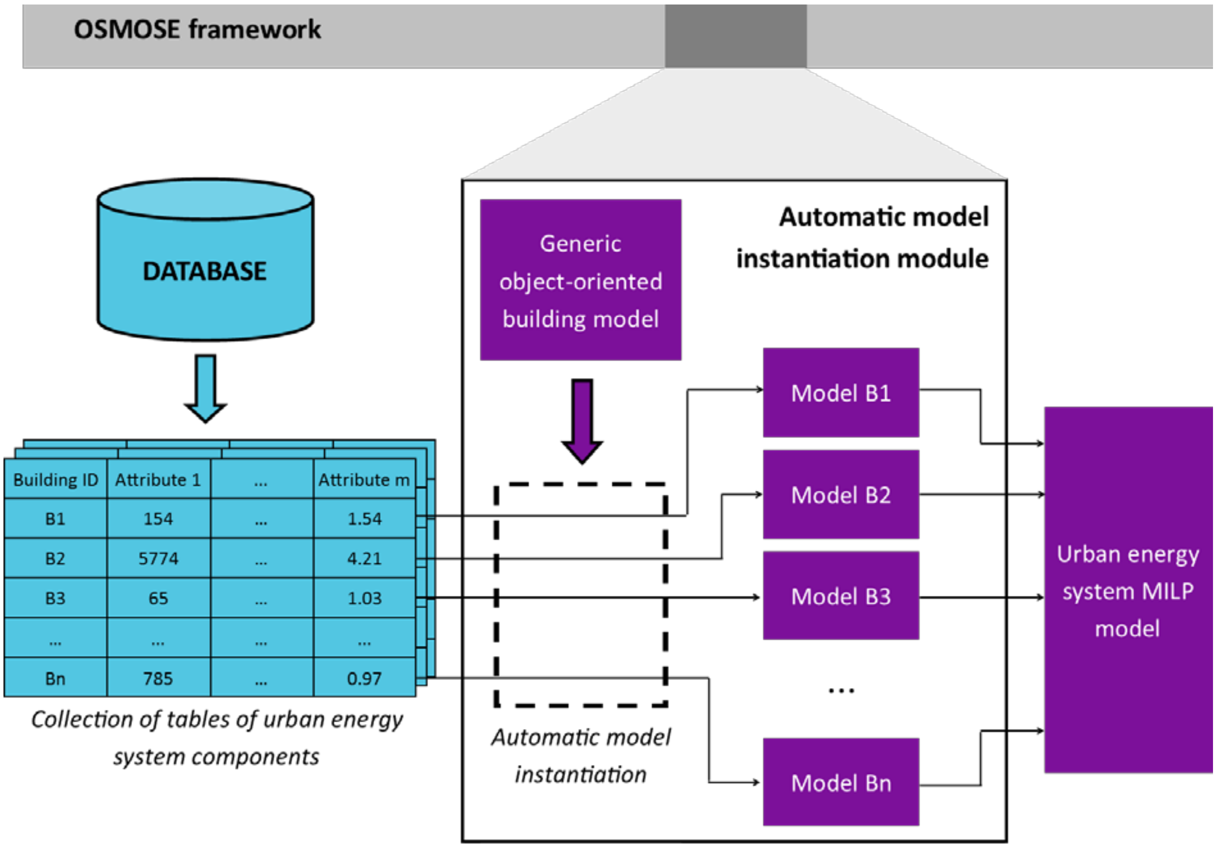

Figure 5 - Automatic urban energy system model instantiation module

3.3 Summary

Up to now, a model-based methodology to support early stage local urban and energy planning has been developed and will be the backbone of the future CINERGY platform. The methodology consists of two main steps. In the first step, which cannot be automatized, the planning framework (goals and constraints) is synthesised through the review of site specific urban and energy planning documents. In the second step, this information, combined with the available data of the urban system, is used to generate a Mixed Integer Linear Programming model and an optimisation with respect to the relevant objective is carried out.

The strength of the model is demonstrated by addressing the fivefold interdependencies between social targets, environmental constraints, economic implications, technological feasibility and urban form (Figure 6). Indeed, within the optimisation model, each of these five aspects can be considered either as an objective function, decision variable, constraint or input parameter, although the objective function is unique. In the demo case study, the total cost was considered as the objective function to be minimised.

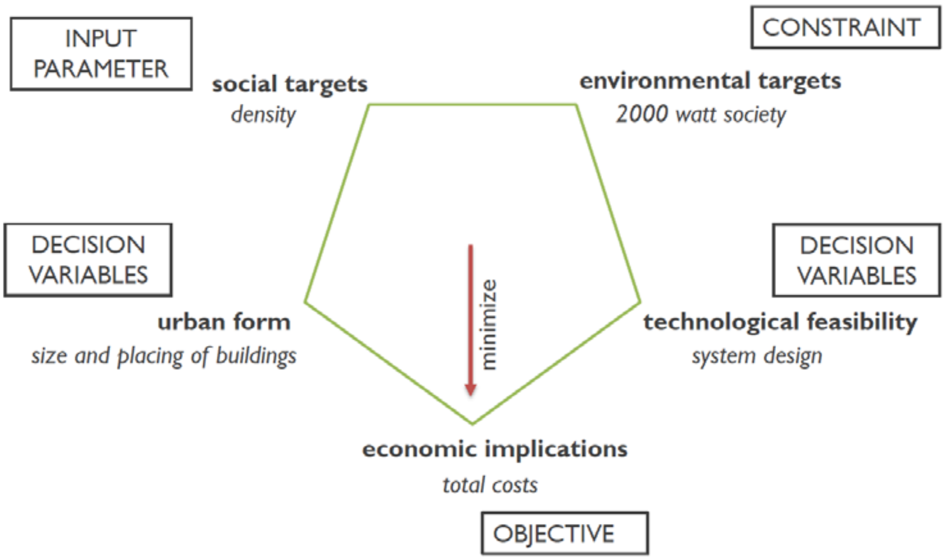

Figure 6 - Depiction of the fivefold interdependencies in the optimisation problem [1]

4. Demonstration

The methodology described in the previous section was developed using data from a demo case study in one of the two partner cities of the project. The case study is presented in [1].

4.1 Demo case study

The demo case study is a greenfield urban development site called “Les Cherpines” located in the suburbs of Geneva (zone 2 on map of Figure 7). It is one of many urban development or re-development project sites which exist in the canton of Geneva, as shown on the map below. The future district will cover 58 ha of currently unoccupied fields and, as a mixed-use “eco-district”, will consist of 3000 residential dwellings and provide space for offices, services and public facilities providing around 2500 jobs. In total, this will add up to 560 000 m^2 of building floor area which are expected to be constructed by 2030. Spaces for parks and biodiversity friendly areas have also been reserved.

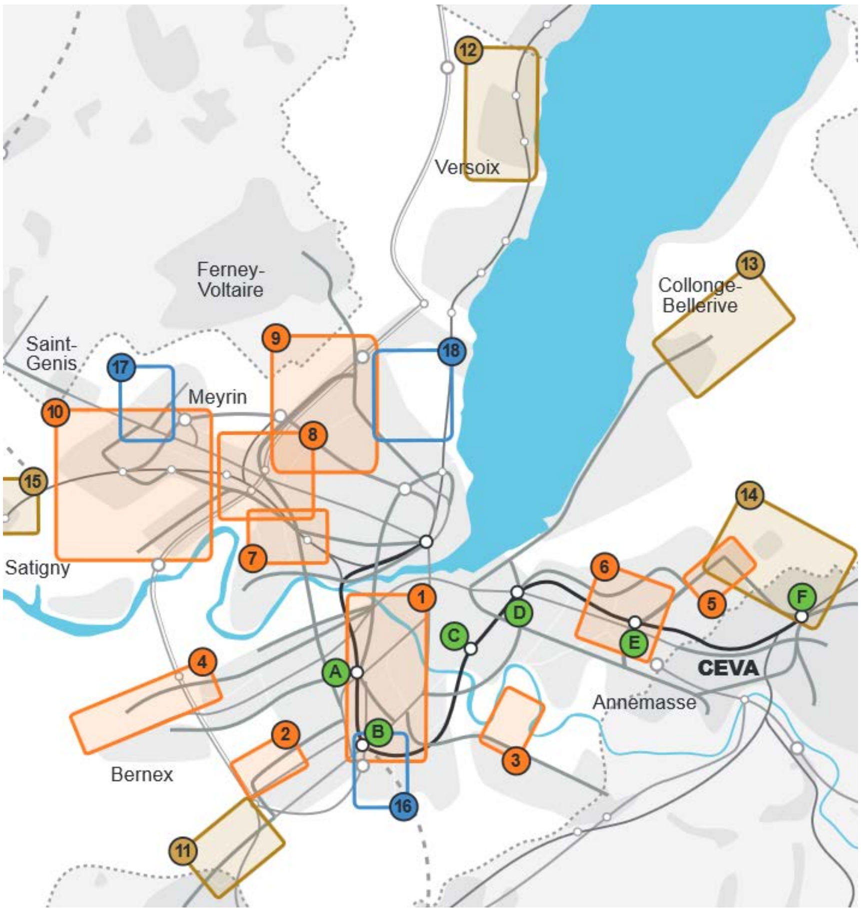

Figure 7 - Map of urban (re-)development projects in Geneva canton [2]

Energy considerations are an important component in the planning of the future district. Indeed, the project aims to support the cantonal energy strategy of achieving the 2000 Watts society without nuclear power, implying high objectives for energy efficiency, use of renewable energy sources, and striving for district energy positivity. Additionally, the area is particularly of interest due to a neighbouring industrial zone called “ZIPLO” which provides an important and year-round source of waste heat, especially low-grade heat. This heat could be harnessed through the use of a district heating network, combined to heat pumps when required, to fulfil a substantial amount, if not all, of the heat demand.

4.2 Results

The present methodology and framework described in section 3 were applied to the demo case study. The goal was to identify optimal energy strategies, as well as to simultaneously provide indications on the urban layout.

The urban layout constraints considered in this case study were the following (obtained from planning and legal documents):

- Fixed building density (a sensitivity analysis was performed on this input)
- Maximum number of floors (different value for office and residential use)
- Building footprint (predefined tiles where buildings can be built)

The main energy constraints consisted in fulfilling:

- Yearly energy demand for each building (heat and electricity) according to the MINERGIE-P norm
- Design heating power requirements for each building
- Covering X % of the energy supply with renewable energy sources (75 % for the “2000 Watts Society”). A sensitivity analysis was also carried out on this parameter.

The decision variables were:

- Type, size and location of the energy supply systems (list of options in Table 1)
- Urban layout: distribution (on which tiles), use (residential/office) and size (number of floors) of buildings
- Layout of district heating network pipes

Table 1 - Energy supply technologies considered

Decentralised gas boiler
Decentralised ground source heat pump
Centralised gas boiler
Centralised combined heat and power plant (CHP)
Centralised heat pump (on industrial waste heat)
Solar PV (on building rooftops)
Centralised Heat Transfer Station (on industrial waste heat)
Decentralised Heat Transfer Station (for each building)
Heating network pipes

The objective function to be minimised was the total energy system cost, including both investment and operating costs. It is to be noted that the construction costs of the buildings themselves were not taken into account.

A result of applying the methodology is shown in Figure 8. This graph shows the evolution of the total annualised energy system costs with increasing density, for different fixed renewable energy sources (RES) targets. The boxes indicate the density from which all tiles host a building (for each RES target). The line style indicated the shift from a decentralised system (dotted) to the use of a heating network (plain).

As observed from Figure 8, there are density thresholds above which costs start to increase faster with density. This is due to the changes in the energy supply system chosen. In the first part, decentralised ground source heat pumps, gas boilers and solar PV are favoured. This can be seen in Figure 9, where the density is such that not all tiles are occupied by buildings, and where all buildings are supplied by fully decentralised options.

As soon as all cells are occupied, decentralized options can no longer provide sufficient RES energy: no more roofs are available for additional PV panels, and the heat pumps’ power demand would require power from the grid beyond what is acceptable from the RES constraint. This tipping-point in density makes the centralized district heating using industrial waste heat the next cost-optimal option which allows the RES target to be achieved, by providing a more energy efficient solution than the decentralized options. The buildings closest to the feed-in point of the industrial waste heat are connected to the heating network first, as this minimizes infrastructure costs (see Figure 10), despite the fact that a heat pump is required to increase the temperature level. At this point, the urban configuration further adapts itself such that the taller buildings are clustered together in the area closest to the source of industrial waste heat.

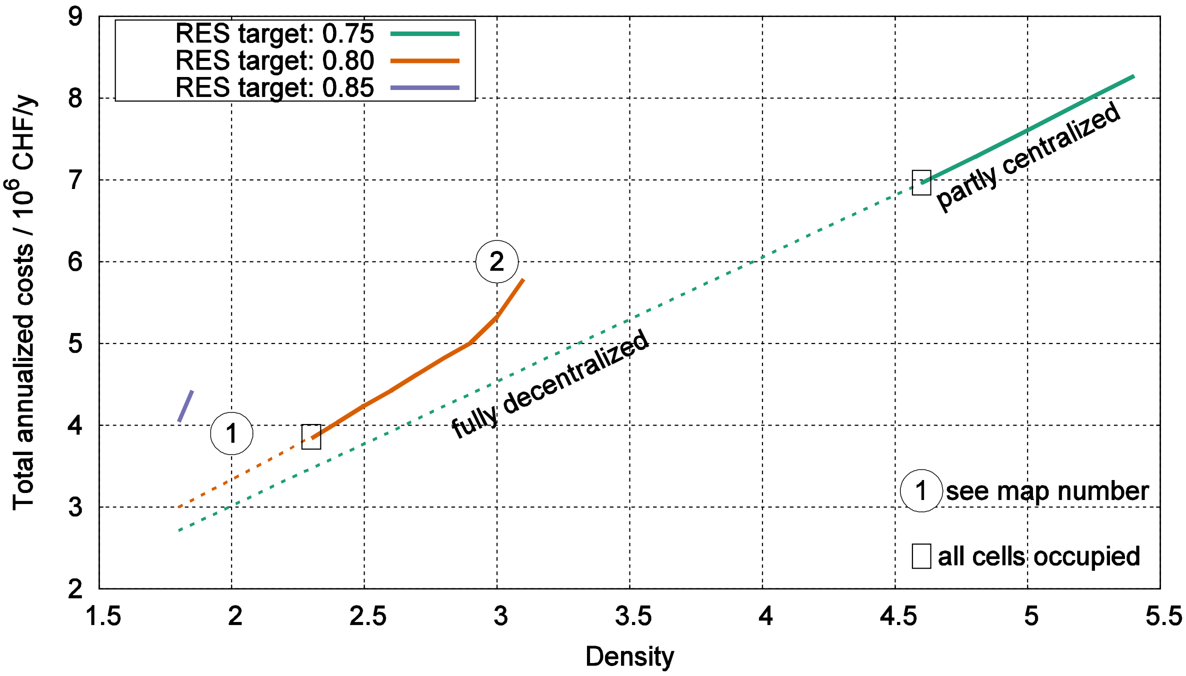

Figure 8 - System costs for different RES targets, over varying density [1]

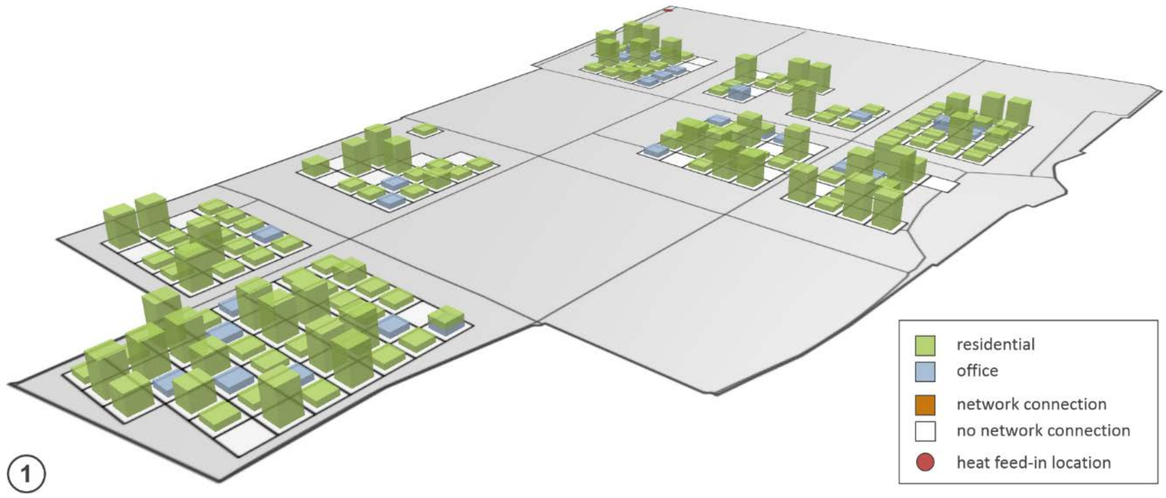

Figure 9 - Map of case study, for a density of 2 [1]

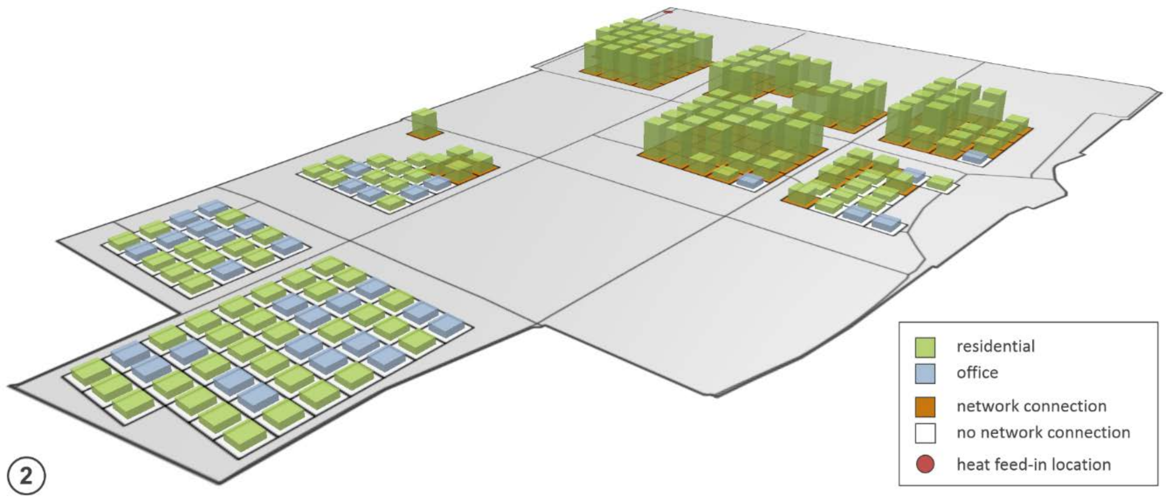

Figure 10 - Map of case study, for a density of 3 [1]

The main levers in shaping these curves were identified to be the achievable share of solar PV area and the waste heat price. For example, a waste heat price of 0.035 CHF/kWh is found to be the threshold up to which a network is installed even for low densities, regardless of the RES target.

4.3 Outcomes

Applying the methodology to the demo case study has allowed to better understand and reinforce links between generally fragmented sectors, scales, project phases and disciplines, paving the path to more integrated urban and energy planning. In particular:

- Regarding the link between sectors, the proposed methodology represents a useful way for planners to anticipate effects of their decisions on the energy strategy, e.g. regarding density on the energy system design. In this sense, the link may be consolidated with a better understanding of the two sides of the planning scope: urban and energy aspects.
- Regarding the link between scales, the model-based approach supports decision simultaneously on the building and the district scale. It thus allows to depict interdependencies between them, which, for complexity reasons, may be difficult to grasp with mere intuition.
- The third link (between project phases) can similarly be improved with a MILP approach, which has proven effective to quickly generate information from which calculations can be performed. This represents an improvement from more general approaches which rely on rough approximations and assumptions regarding the unknown information.
- The link between disciplines (planning and mathematical programming) was also successfully established, as the planning framework and constraints could be modelled through mathematical expressions in line with legal and practical constraints.

5. Next steps

The methodology that has been developed is the first step and backbone of the future decision-support platform for urban energy planning. The next steps to reach this goal can be broken down into:

- Improvement of the current methodology and model
- Coupling of this model with the other models developed in the project

- Coupling with a master multi-objective optimisation
- Representation of results and decision support methods
- User interface
- Test on other case studies

5.1 Improving current optimisation model

Firstly, several improvements can be made to the current model. This ranges from adding other urban planning constraints to defining new technology models which would be in competition with the current ones (e.g. fuel cells, CO2 network, etc.). These will be dependent on the case study site, whether considering the local renewable sources (industrial waste heat, geothermal, etc.) or the local urban planning constraints (density, etc.).

Additionally, beyond case-study dependent aspects, modeling every aspect of complex problems such as urban energy system planning is generally impossible. In this regard, interactive methods for data exploration and visualization can be beneficial to allow the integration of expert knowledge and experience with simulation and optimization tools. The foreseen decision-support platform should therefore allow the user to interactively activate and parameterise a certain number of pre-defined constraints and technologies, which shall in turn influence the optimization process. In this way, the proposed tool would become an ongoing iterative process in which the discussion between planners, energy experts and modelers could be achieved.

5.2 Coupling with other models in CI-NERGY

Regarding the coupling with other models, different options can be considered, as was presented in the vision (see section 2). These can be summarised by the two following categories:

- Post-optimisation validation
- Pre-simulation of optimisation model components

In the post-optimisation validation, promising results of the optimisation are chosen and modelled in more detail. The co-simulation toolbox developed in the project would then be applied to evaluate the technical feasibility of the solution and indicators recalculated with more precision. Ideally, the detailed simulation models would be automatically instantiated from the simple optimisation models. For this purpose, a library of predefined simulation models would have to be created, with each simulation model corresponding to an element of the system (e.g. building model or network model). A CityGML model generator could also be used here to generate random building geometries respecting the main characteristics obtained by the optimisation. This would in turn be used to instantiate the building simulation models, and was done by ESR3 and ESR7 [3].

In the second category, some components of the system are instead simulated prior to the optimisation itself based on input data provided. For example, the building energy demand could be calculated using simulation beforehand (e.g. models developed by ESR7 [3] and ESR9 [4]). The limitation of this approach is that the urban characteristics (layout, form and usage of buildings) would have to be defined upstream of the optimisation, thus not allowing to study the simultaneous impact of the energy system and urban form as was done in the demo case study presented in section 4. However, this could be solved by having a heuristic master optimisation encapsulating the MILP optimisation model and pre-simulation, which is the next point addressed.

Finally, it is also possible to imagine combining both integration modes.

5.3 Coupling with a multi-objective optimisation

The two level master-slave optimisation procedure is represented in Figure 11. At each iteration of the master optimisation, which is based on an evolutionary algorithm, a set of master decision variables are sent to the so-called slave optimisation, and thus modifies the parameters of an MILP sub-problem. The mono-objective deterministic slave optimisation is carried out, and the results are sent to a post compute function which calculates the objective function of the master optimisation as well as any other indicator of interest. The objectives are sent back to the master and evaluated, and the procedure is then re-iterated.

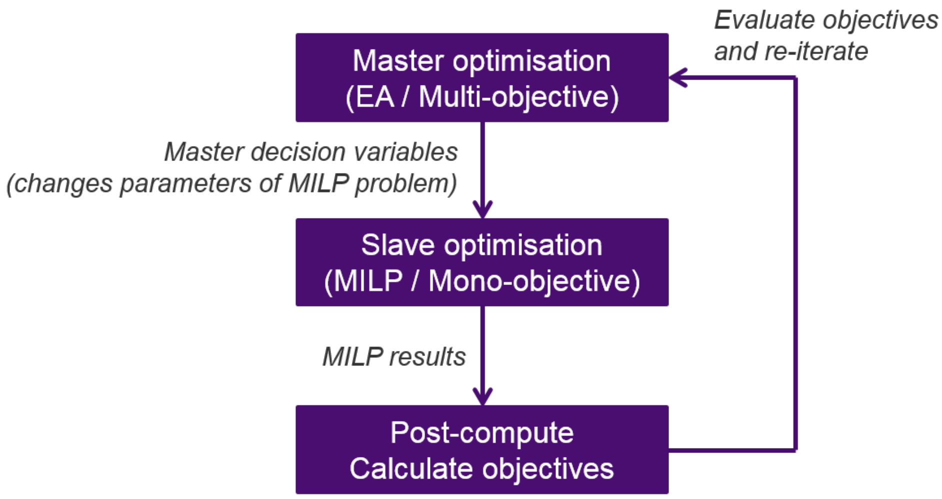

Figure 11 - Master-slave optimisation procedure

The advantage of this approach is that decision variables with impacts that are difficult to linearize can be taken into account (e.g. having a variable heating network temperature). The same applies to non-linear objective functions. Additionally, a pre-simulation can be carried out at each iteration of the master optimisation, prior to the MILP optimisation (see section 5.2). In particular, this would allow to define the urban form by master decision variables, and therefore perform the building demand simulation in between both optimisation levels.

The multi-objective optimisation functionality is already included in the Osmose package and could therefore easily be adapted to suit our needs.

5.4 Other improvements

A major focus of any decision support tool is to provide an adequate representation of the results. Indeed, it should be adapted to the level of understanding of the decision maker. Going beyond simply result representation, multi-criteria decision aid (MCDA) methods can be applied. MCDA is a set of methods to evaluate alternatives based on conflicting criteria according to decision maker's preferences. Work in this field is carried out by ESR1, in particular to help select and apply appropriate MCDA methods to support the identification of preferred solutions resulting from the optimization.

A user-friendly graphical interface for the platform would be nice, but it is not foreseen within the scope of the project. A preliminary interface shall be provided by the use of interactive data visualization and exploration tools (e.g. parallel coordinates) discussed in section 5.1, however, its further development could be one of the post-project actions if there is a will from some of the partners to further develop the tool.

Last, but not least, the platform needs to be tested on a variety of other case studies in order to further validate the methodology.

6. References

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