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Towards pre-dimensioning of natural gas networks on a web-platform

[A platform dedicated to urban energy management: achievements and further developments]

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Background: The MEU platform: a tool dedicated to urban energy monitoring and planning

Due to high level policy decision, energy systems, especially at local scale, have considerably evolved during the last ten years. European Union for example decided in 2008 the 3x20 strategy: decrease CO_2 emission of 20%, increase energy efficiency of 20% and share at least 20% of renewable energy considering the global energy consumptions, at EU scale and since 2020. Such decision had a direct impact on local energy systems, in terms of demand as well as in terms of supply: buildings refurbishment or more efficient devices implementation, saving energy ; decentralized energy production, based on renewable or distributed energy (e.g. : Combined heat and power); substitution of fossil & fissile fuel by renewable or CO_2 free energy.

This pressure, coming from different level regulation [Cherix et al., 2009], combined to the availability of high efficiency and renewable new technologies increase the number of possible solutions to achieve a defined territorial objective, like EU 3x20 applied at local scale through the Covenant of Mayors [Covenant of Mayors, 2008]. The solutions, which local decision makers have to compare are more and more complex, tackling spatial and temporal distribution of energy resources and demand, considering multi-energy centralized and decentralized technologies. Computing becomes necessary as a decision support system, taking into account as many solutions as possible, and benchmarking them based on different relevant indicators (primary energy consumption, CO_2 emission, share of renewable energy). Such a computation scheme needs a large energy technology model library, as well as huge quantity of "up to date" territorial energy data [Blanc G. et al, 2013].

In parallel, Information and Communication Technology science highlighted the potential of Smart Cities, to better collect, process and store territorial data including energy data. This approach can strongly support the way that local administration, as well as utility industry, manage and share territorial energy data. The use of such smart cities energy data enhance the knowledge of the local energy system "state of the art", allow the monitoring of local energy system performances, and support the computation of future energy systems scenarios as help decision tool.

The Urban Energy Management - MEU - Web platform, combines effectively smart cities energy data on one hand, and energy technologies and infrastructure simulation on the other hand, for both urban energy planers and utilities. It contains buildings physical description, energy conversion systems inventory and utilities available energy consumption data (electricity, natural gas and district heating). The availability of a simulation tool in the platform allows estimating the demand and consumption of not filled building consumptions (oil, wood, etc.). All data are spatialized, increasing the feasibility of designed solution because integrating reality constrains. The main features published in the platform are the following [Capezzali & Cherix, 2012]:

- GIS-enabled cartographic user interface, as main working environment;
- Quantitative computation of a whole range of energy-related indicators of an entire urban zone, either at the building/demand or at the energy supply level, including GHG emissions;
- Access to completely hands-on planning of urban zones, by way of the creation and quantitative evaluation of scenarios encompassing desired improvements in terms of both energy demand and supply;
- Continuous annual monitoring of energy flows, consumptions and related actions, such as building retrofitting or renewable energies integration, through a time-dependent database.

For utilities and especially gas industry, data and energy conversion models included in the MEU platform have a high added value, considering network design and market aspects. The cooperation between local authority and utility company allow sharing relevant data, owned partially by each one of partners but useful for both of them. Consumption data are necessary to monitor GHG emission at territory scale [Blanc et al. 2013]. Specification of oil supplied buildings, as well as urban plan development, are key information for energy networks companies.

The goal of the MEU+ project was to prototype the integration of a network simulation module in the MEU platform. Considering the territorial energy planning decided by the local authority, what will be the influence on the network design, what are the main risk for the security of supply, as well as in terms of profitability. For city, considering the sourcing strategy of local gas supplier (natural gas, biogas, etc.), what will be the impact in terms of global GHG emissions. The goal of such integration is to connect network simulation to real data (spatial, topology, consumption) database, filled both by local administration and utility. Eventually, utilities will be able to evaluate what are the impact of each new building connection or building refurbishment on the network design and operation.

This article explain how this integration has been designed in terms of method and user interface. First software development and simulation results are presented in the end of the paper.

Aim: A new "Natural Gas Networks" module built for energy utilities: MEU + Project

The objectives of this project within the larger MEU endeavor were to : i) Create a platform gathering topological and geo-referenced data; ii) Develop a gas network pre-design/planning methodology, connected to demand characteristics embedded in MEU and including gas supply for buildings in a selected area; iii) Interface with gas distribution operators existing tools and add new functionalities within a single platform; iv) Include gas distribution system operator constraints and operational realities in the pre-design/planning process.

The idea is to create a new module allowing to test different pre-designed scenarios, to simulate their behavior in order to calculate and display dynamics data for the considered network. We are targeting to create new functionalities for utility engineers in order to help them to design new network and expand existing network or for system diagnostic purpose.

Our aim is to enable users to create new buildings, add or delete structural punctual elements and pipes, modify installed heating power for an existing building and add feed-in of biogas. The resulting new network will be then tested and its behavior simulated to see if the production and import capacity matches the demand and if the pressure is adequate in reducing stations to pipe the gas to consumers.

The network tool will be useful to determine if a new district can be connected to the existent network or if the actual network need to be densified. It will also help to estimate the effect of a non-operational (or out of service?) pipe, due for example to road maintenance.

Methods: The MEU platform

Nowadays, a large amount of energetic data are available in smart cities. Such data exists in different forms and most times are unstructured. The MEU GIS web-platform enables to structure, centralize, make durable and display all energetic data link to energy demand and supply at the urban energy scale with building details as well as energetic network details (building's characteristics, energy conversion technologies, energetic consumption and supply networks).

Estimative demand models are linked to real consumptions (available data from energy utilities) for example to estimate building oil or wood consumptions in order to describe a whole urban area and realize energy-climate results at both building (demand) and supply levels. Two estimative demand models are developed on the MEU platform. The first one is based on statistic and specific annual thermal energy consumption depending on the construction period and SIA 380/1 building affectations [Blanc et al., 2013]. The second one using the CitySim solver [Kämpf & Robinson, 2009], a very detailed building physics software developed by EPFL which simulates dynamic building energy demand at hourly scale (taking into account material layers of the walls, solar gain and the influence of nearby horizon, etc.). Energy and environmental yearly indicators can be displayed either as detailed tables or as maps and easy-to-visualize symbols.

The data contained in the MEU database faithfully represent the current state of a given urban zone or of an entire city at a given time (year temporal scale). Then data collected over the years can be stored in the MEU database, as data collected by engineers during building energy audit, to improve data quality. In that sense, a four level (0, 1, 2 or 3 stars) metadata rating system was implemented to account for the variation in input data quality (default, estimated, simulated and measured). In the future, smart meter consumption data will be inserted in the MEU platform, the data structure allowing to manage hourly data and correlating it to climate data as solar radiation or heating degree days.

Collecting data over many years, the MEU tool allows precise monitoring of energy demand and supply evolution over time, allowing city planners and utilities evaluating the impact of the undertaken actions. Furthermore, the creation of scenarios based on a given actual year allow a quick comparison of different energy conversion scenarios for different technological measures (for example energy vector modification: oil boilers substitute to gas boilers) or the evaluation of refurbishment strategies on the energy demand.

The MEU platform and its functionalities have been built in a completely bottom-up approach, based on the requirements and concrete needs of the partner-cities and multi-energy utilities. The following main blocks are detailed below [Capezzali et al., 2014].

City buildings represent the central element of the working environment of the platform, since they constitute the basic data node for registering energy conversion systems and their respective consumptions, on top of energy networks - see block "Bâtiment" (Buildings) on the figure below. Indeed, the main functionalities of the platform are made available by way of the building footprint on the working map.

Physical and structural data of the buildings as heating surface, typology, walls and windows parameters - are also integrated, based either on default values depending on the construction year (imported from the Swiss Federal Registry of Buildings, RegBL) or on collected values entered manually by the user (e.g. following an energy audit).

In all buildings, n≥1 energy conversion technologies - see block "Technologies" (Technology) on the figure below - are present and deliver m≥1 among the four basic energy services, namely space heating, domestic water heating, space cooling and electricity services. The distribution of services can be introduced manually or computed by CitySim, connected to the platform through a customized web-service.

The MEU platform offers a large spectrum of technologies, from heat pumps to various types of conventional boilers down to solar equipment and co-generation units, which can be fully characterized by the user. Shared decentralized energy conversion systems can also be taken into account (e.g. a boiler linked to two buildings), leveraging on the GIS functionalities embedded in the tool.

As far as they are available - hence the importance of having multi-energy utilities as early project partners, the yearly measured energy consumptions of each building - see block "Consommation" (Consumption) on the figure below - are stored in the MEU database. For buildings without measured consumptions, the tool will evaluate the energy demand for each service, and then convert them into final energy consumption using the technologies library

Geo-localized energy networks – district heating, electricity, natural gas, free cooling, as well as non-energy networks such as drinkable and used waters – can be added as additional maps to be visualized on the MEU platform.

All energy vectors (both network-based, as well as oil or wood) are characterized by primary/renewable energy and GHG factors imported from KBOB database [KBOB, 2014]. For network energies, network losses, as well as different supply contracts can be introduced and fully specified on the platform, in order to take into account the efforts of the energy utilities towards renewable energy sources and increased energy efficiency, e.g. on natural gas or district heating networks [Cherix, 2010].

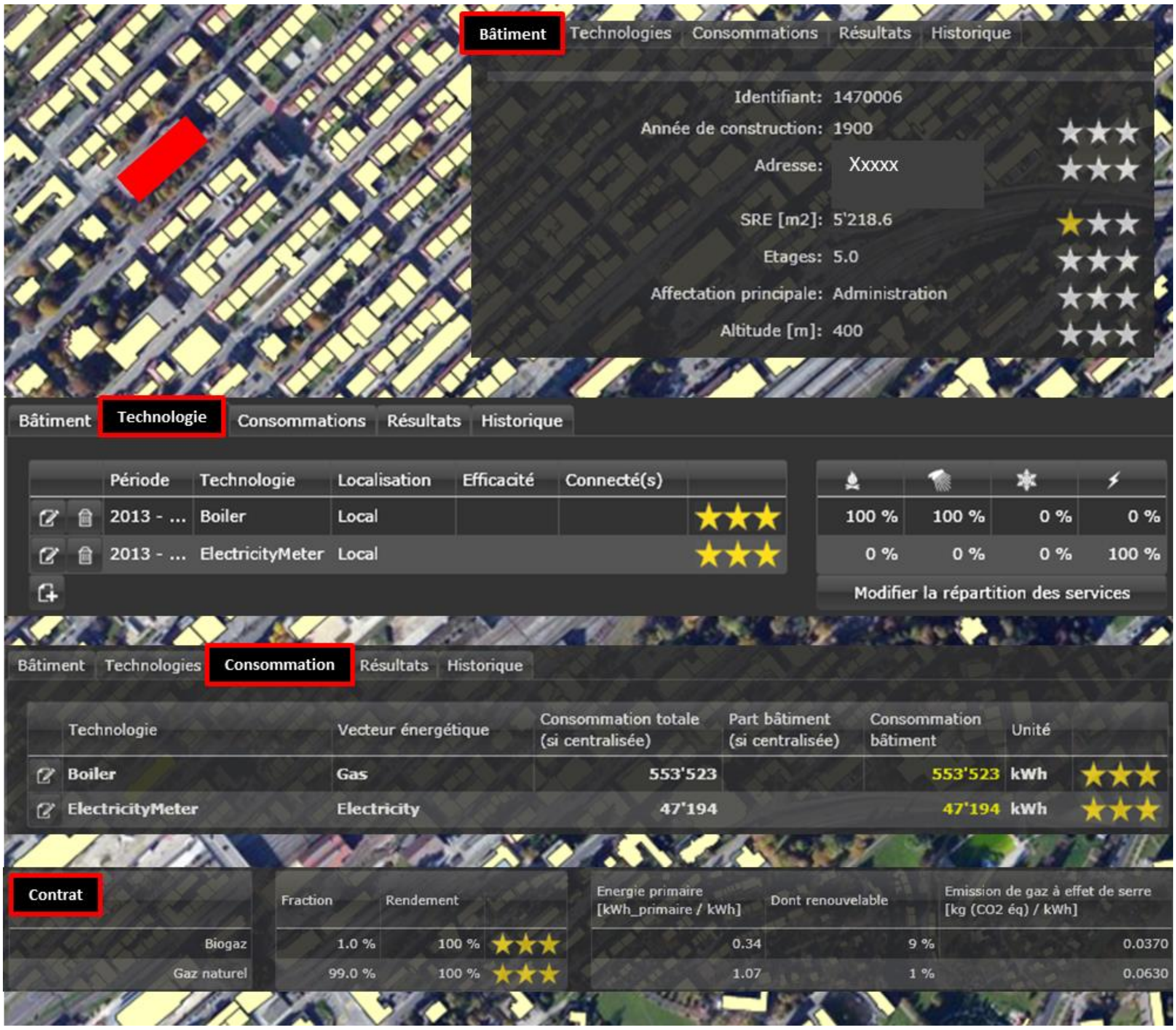

Figure 1 : Main blocks display (Platform only available in French)

Methods: Gas network integration

Dedicated data model creation

The database is the central part of the MEU platform. It allows to store data coming from different source and to make it available for display, indicator computation and network simulations. Within MEU + Project, the pre-existing data model covering buildings and conversion technologies has to be extended in order to incorporate networks. The data model's architecture is a key factor for the implementation of the platform's functionalities and was therefore methodically elaborated.

Three constrains were identified for the network design sub data model. 1) Integrate data needed by network energy providers. 2) Integrate topological data needed for network simulations. 3) Comply with existing norms and good practices in terms of network representation.

Based on a bottom up approach, interviews were conducted with industrial partners in order to identify their needs in terms of data accessibility and display. These needs were added to the inputs needed by the simulation tool developed in parallel and translated into objects and attributes, based on the technical guidebook n° 2015[1] given by the Swiss Society of Engineers and Architects (SIA).

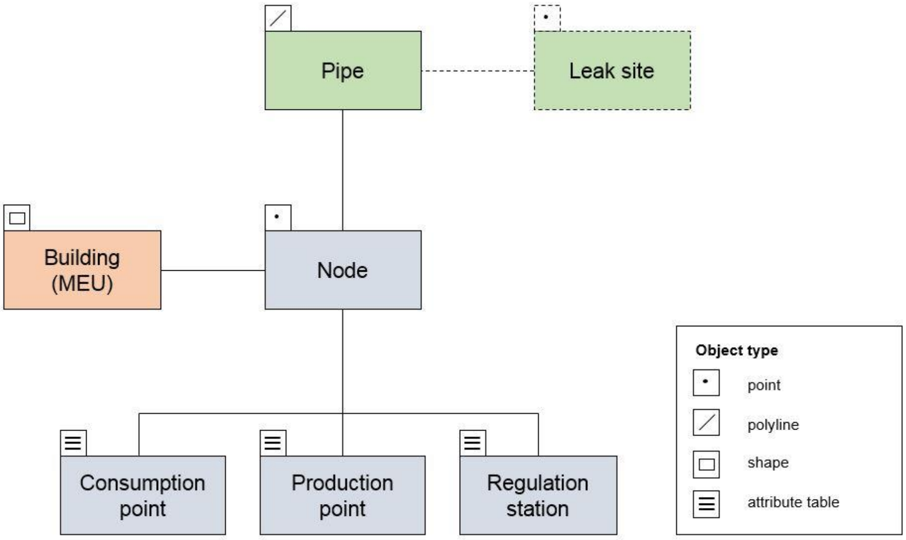

Figure 2 : Network data model objects diagram

[1] *GEO 405 – Catalogue de donnée et de représentation de conduites souterraines*, SIA, Cahier technique 2015, Zurich, 2005

The resulting data model contains two "geographical" objects: node (point) and pipe (polyline), as well as three "attributes table" objects that can be assigned to a node to form a consumption point, a production point or a regulation point. This basic model can be extended depending on the user's needs.

Network edition tool development

The need of a network edition tool comes from different consideration:

Gas network data, owned and managed by gas distribution industry, are not standardized, at least in Switzerland. Each gas company could have his own information system and data structure. Then, gas network data, received from gas utilities, need some processing to match with the data model described previously. For example consumers concepts (consumption points) are not matching: the network data model developed for the platform MEU requires a completely distributed and topological pipe system from pressure down station to consumers whereas, e.g. in some partners gas utilities data, consumers are only considered as flow rates taken out at a length percentage of the main pipe (see next figure). Complete topological aspect of the data also have to be confirmed to suit the platform data model. Data also needed to be visually verified to check if the gas network is coherent, represented as a connected graph.

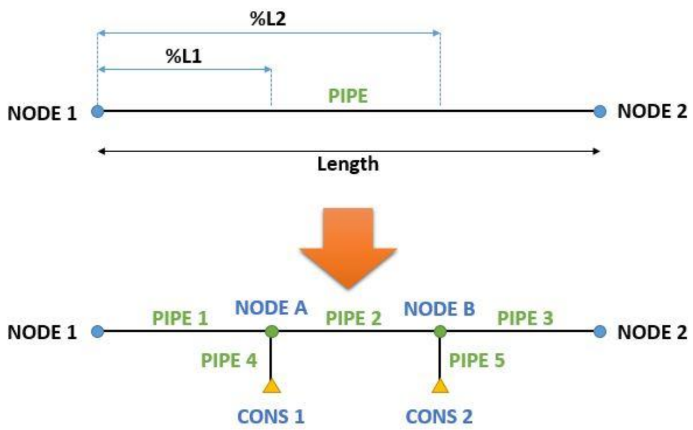

Figure 3 : Data modification

The main idea of the MEU+ project is to create, test and validate new scenarios for gas infrastructure. It begins with the edition of existing networks or the creation of a completely new network.

Gas utilities project partners actually work on two completely separate tools to handle gas network modification test and validation. The first one, based on a very precise "draw" of the existing network, ensure the spatialized aspect of the data, necessary for network maintenance and intervention, but it can't deal with topological data or flow simulation. The second one (ex: NEPLAN®) is flows simulation tool which is not design to manage GIS data. The need of a tool integrating both GIS data and topological data arise from Gas utilities project partners, simplifying the management and use of network data.

Previously described needs and MEU platform (with new modules) compatibility induce some requirements for the network edition tool. A tool with a quickly and highly adaptive technology is needed in order to be adapted to specific data modification requirements from different gas utilities network database with diverse data model and specifications. Map visualization, with buildings display including gas network as layer and network objects attributes access, are essentials functionalities for scenario editing and existing network apprehension. The simplest and more user-friendly way to edit network is to add, delete and drag&drop network element directly on the map. Import and export network data model have to suit the global data model in order to keep the compatibility with other MEU platform networks modules.

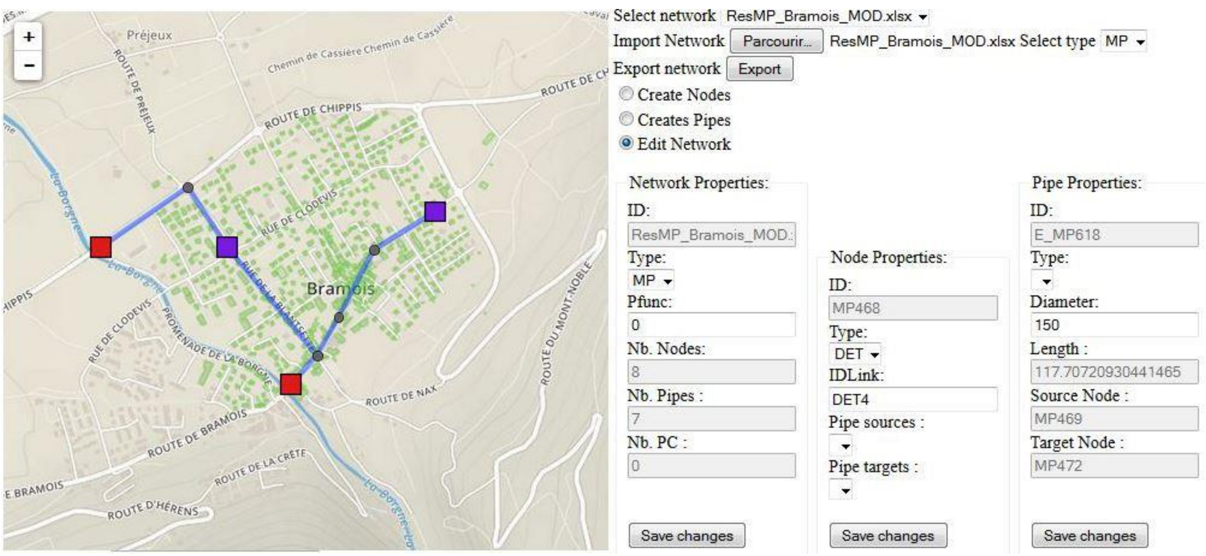

Figure 4 : Network edition tool

Network flows, and pressure simulation device development

Tool specification; assumption and physical modelling; and integrated solving simulation will be detailed below:

With the aim of define specification of the network simulation module, typical use cases have been elaborated thanks to the interview of gas utilities project partners. Basically, they need a tool to address in a faster and more reliable way gas network problematics, such as:

- Building connection
- Pipe design
- Consumption/Production or network path modification impact
- Power or max flow rate available at a network point estimation

In order to answer such problematics, an experiment/error method appeared to be the most suitable method to respond to the panel of diverse gas network design use case without using any optimization algorithm. An experiment/error method is based on an iterative validation or invalidation of design parameters iteratively modified by the user. The validation goes through the impact analysis of the design parameters on the network behavior, addressing simulation purpose.

Even if such gas network simulation tool already exist [NEPLAN®], the choice have been made to create a new tool - GIS-oriented - to integrate it easily in the existing structure of the MEU platform.

Hourly buildings demand load estimation are available in the MEU database. Current gas network design method are mainly based on a maximum demand analysis. The idea to improve the precision of the given results is to perform an hourly network analysis via simulation. This hourly simulation allow users to dispose of more precise data and help them to design a more economic and energy efficient network, minimizing safety factors. Such hourly simulation also support network operation diagnosis, calculating network state for any operation point, compared to network measurement on a specific time.

Import and export network data model also have to suit the global data model guarantying the compatibility with other MEU platform networks modules.

Several assumptions have been taken intending to create a network flows simulation tool able to perform a simulation for a complete urban area in an acceptable computation time.

- Multiple steady state sequence

A pressure wave move at about 300 m/s (sound speed in the air at 1 bar), establishment of a steady state for a 100 m pipes will take about 0.3s. As the simulation tool is built to perform hourly simulation, the assumption will be that each simulation step will be considered in steady state, forming a multiple steady state sequence. Each step result (i) will be use as initialization values for the next step (i+1). Knowing the fact that evolution of gas network behavior between two steps is quite limited, this re-use of (i-1) steps results allow, for each calculation step , to provide close initial values and then to converge more rapidly. A side effect of this method is that it avoid local minimums with values far from precedent calculation step and real network behavior. Only first calculation step take a longer time to cover a larger range values for network variables.

- Compressible fluid and perfect gas

Temperature influence on gas density at considered constant pressure (<5 bar) is too important to be neglected, the hypothesis of a non-compressible fluid is rejected. Moreover considered pressure are included in the pressure range where the behavior of the fluid/gas is similar as a perfect gas.

- Kirchhoff's first law on molar flow

Network topology and compressible gas behavior allows to use Kirchhoff's first law equivalent on molar flow for each gas network node. Gas molar flow is conserved at each network node.

The simulation is based on a perfect and compressible gas model. The composition of the gas is considered as pure methane. The model include linear pressure loss equation and is built on a conservation of the molar flow rate through each node. Heating power are calculated for each building using a MEU module building physics software which simulates the energy demand by correlating real annual data from utilities and hourly simulated data.

The resolution of the equations system for each node of the network is made by an integrated optimization MATLAB® function (fsolve) using the Levenberg-Marquardt algorithm. It allows to determine a stable state for considered variables in each point of the network at each simulation time step.

Simulation results display and analysis

Georeferenced representations of networks and related data is a key feature of MEU+. It is built up on the existing GIS based visualization interface that allows users to activate layers displayed on top of an ortho-picture map and access data by clicking directly on the objects.

Concerning basic network representation, pipes are shown as segments and nodes as points or pictograms. Width and color of the entities may vary depending on the type of network (mid/low pressure, carrying, delivery, etc.). In order to avoid over-charging large scale maps, three levels of detail display have been defined depending on the zoom.

In addition to the basic representation, thematic maps can be displayed according to user needs. Segment width variation and color scales could be used to highlight aspects of the network state such as flowrate, speed, pressure or location of leaks. Other representation, taking advantage of the building database, highlight new market opportunities like oil heated building within a certain range of the network, or building with higher needs.

Access to network component attributes is done by clicking the object on the map. A pop-up window displays all information linked to the object. Data are organized in tabs for convenience of use. A first tab displays general information like identification code, coordinates, construction year, etc. A "modify" button allows user to modify the content. The "results" tab displays the simulation results. The "documents" tab shows a list of documents (reports, schematics) related to the object. The "history" tab shows the history of modification. Depending on the object type, additional tabs are used to display specific information (consumption, production, regulation). The same four level metadata (0, 1, 2 or 3 stars) is also used to qualify data quality of networks components.

A global network window allows to display synthetic network values like annual volume distributed, global pipe length, average network age, energy vector penetration rate, biogas share, delivered power, etc. as well as graphical representation of the whole network or a selected area.

Results: Prototype of a gas network simulation module

The first step for the creation of those new functionalities consists in developing an operational prototype module for gas network management. Based on this development, calibration and validation test have been done.

First, state parameters of the analysed network have to be defined and integrated by the user, defining the calculation scenario based on the actual installation, pipes and structures.

Then come the simulation phase. The user can choose the step, the duration and the period of the simulation. The studied system is limited to medium pressure (< 5bar) and low pressure networks (< 0.050 bar). Transport pipelines between 40 bar and 50 bar are not include in the model. The simulation calculates pressure, molar flow rate and density of gas for every node of the network.

Output and validation of the model

The raw results of the simulation are then exploited and converted to graphics. The user can choose nodes and the associate variable (pressure, speed, flow rate, etc…) which are most relevant for his analysis and which require to be added to graphics.

In order to test and validate gas network model with associated technical assumptions, a sort of "basic blocks" method have been developed. Basic and simplistic network structures have been created and implemented based on real network topology analysis. Those "basic blocks" are design to simply cover every possible micro-structure of a gas network. Overall model computation and simulation have then been made for each "basic block" structure and the model core code have been adapted to suit every one of those miniature network (see some example on the below figure).

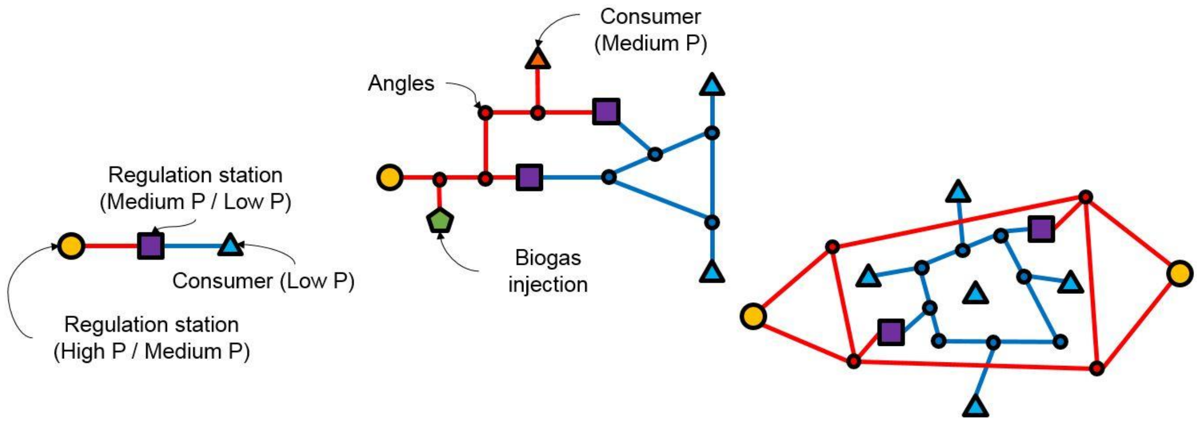

Figure 5 : Basic blocks examples

The model is currently tested for big scale network simulation using a comparison between the network simulated behaviour results and NEPLAN® simulation results on a real neighbourhood. The results of this validation will be published in a next paper, once they will be obtained and analysed.

Network and simulation result user Interface

The basic network representation is functional for the test zone. The three level zoom dependent display is not yet implemented in the prototype version, elements showing on the map are to be manually selected by the user. No thematic representation has been implemented so far. The pop-up windows are functional however the contents displayed in the tabs is limited to basic information. The data base is developed and operational but the data concerning the network are still under validation process. The network balance window has not been implemented yet. A workshop with industrial partners is planned to validate the specification that will be implemented.

Figure 6 : Platform various popup (Platform only available in French)

Conclusions

The MEU platform is currently undergoing broad code refactoring, in order to increase robustness and reliability. New functionalities regarding energy networks and, in particular, natural gas networks, are simultaneously developed and tested. MEU tool users from cities and energy utilities will thus be able to perform detailed network pre-dimensioning computations, based on all smart cities territorial energy dat. The MEU platform allows to display a precise picture of an area with consumption and energy balances. Tomorrow, it will open the gate to high added value data exchange between different energy actors.

Described tools and platform aims at bringing more transversality in territorial energy planning and management. It will foster urban energy networks analysis and design by precise description and study of fluids flows and energy exchange through energy infrastructures. Such technological and methodological advances will help; with further developments and integration of power and district heating/cooling networks; modelling, simulation, improving design methods and comprehension of global urban energy metabolism and territorial energy systems.

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