Facilitating model reuse and integration in an
urban energy simulation platform

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Abstract
The need for more sustainable, liveable and resilient cities demands improved methods for studying urban infrastructures as integrated wholes. Progress in this direction would be aided by the ability to effectively reuse and integrate existing computational models of urban systems. Building on the concept of multi-model ecologies, this paper describes ongoing efforts to facilitate model reuse and integration in the Holistic Urban Energy Simulation (HUES) platform - an extendable simulation environment for the study of urban multi-energy systems.

We describe the design and development of a semantic wiki as part of the HUES platform. The purpose of this wiki is to enable the sharing and navigation of model metadata – essential information about the models and datasets of the platform. Each model and dataset in the platform is represented in the wiki in a structured way to facilitate the identification of opportunities for model reuse and integration. As the platform grows, this will help to ensure that it develops coherently and makes efficient use of existing formalized knowledge. We present the core concepts of multi-model ecologies and semantic wikis, the current state of the platform and associated wiki, and a case study demonstrating their use and benefit.

Keywords: urban energy systems, simulation, multi-model ecologies, semantic wiki

1 Introduction

Urban areas are sustained by way of infrastructure networks that enable the movement of energy, water, information, material goods, waste and people from one place to another. These networks are complex within themselves and increasingly dependent on one another [20]. Moreover, their development constitutes a process of co-evolution – the development of one infrastructure may influence and/or be influenced by the development of other infrastructures.
In light of this, and of growing needs for more sustainable, liveable and resilient cities, it is essential that we develop better ways to understand and study urban infrastructures as integrated wholes. To enable this, we need improved methods to optimize and steer the operation and evolution of urban multi-infrastructure systems. Significant progress has been made in this respect – an increasing number of modeling efforts in the infrastructures domain have sought to bridge multiple sectors, disciplines, perspectives and scales [19].

However, several key challenges hinder progress in this direction. Foremost amongst these is the difficulty of model reuse. In addition to their primary role in addressing a specific problem, models are repositories of formalized knowledge about how the world works. Via effective reuse of this formalized knowledge, we can increase the efficiency of future modeling efforts. Via targeted integration of existing models with other (existing or newly developed) models, we can enhance the scope of problems that it is possible to address. In combination, the reuse and integration of models can open up opportunities to address more challenging (e.g. multi-sector, multi-disciplinary, multi-perspective, multi-scale) research questions with fewer resources and less development work.

But reuse and integration of models are difficult for many reasons. Most importantly, models are not definitive representations of the real world, but “leaky abstractions” [21] with limited scopes of validity. It can be a serious challenge for modelers not involved in the original development process to understand the constraints on a model’s validity and the scope of problems for which it may be suited. This problem is compounded when one seeks to integrate multiple existing models.

Progress in understanding and studying urban multi-infrastructure systems hinges partially on our ability to overcome these challenges. In this paper, we address a key one of these challenges – the need for sharing model metadata. Drawing from recent work in the area of multi-model ecologies [1] and urban energy system modeling [8], we describe the ongoing development of a tool to facilitate model reuse and integration in the Holistic Urban Energy Simulation (HUES) platform – an extendable simulation environment designed to facilitate the study of urban multi-energy systems. This tool takes the form of a semantic wiki, applied to enable the sharing and navigation of model metadata.

We continue in the following sections with a description of the multi-model ecologies concept and an introduction to the urban energy simulation platform. We then outline the potential of model metadata and a semantic wiki to facilitate the development of this platform. Building on this, we describe the design and implementation of a prototype semantic wiki. We conclude with a discussion of the future development of the HUES platform, and the role of the wiki within this.

2 Multi-model Ecologies

In fields from environmental studies [14] to biomedicine [5] to national defense [18], the integration of models reflecting different perspectives, disciplines and scales is fundamental to addressing key scientific and practical challenges. Moreover, because of the large effort, time and cost entailed in model development, reuse of existing models is essential to enabling model integration – a reality reflected in the efforts of various communities to facilitate the sharing and reuse of computer models[4, 11].

Approaches such as integrated modeling [22], multisimulation [17] and cosimulation – as well as modeling frameworks [13] and interface standards [12] – have emerged to facilitate efforts in model integration. However, a significant limitation of these approaches, and of many efforts employing them, is their neglect of: (1) the interactions of models with their socio-technical
context, and (2) the inherently evolutionary nature of models and model systems. Changes in the socio-technical context of a model – the technologies and actors surrounding model development – may influence the feasibility of, or need for, model integration. Changes in the composition of a model or set of models – an inherent part of most model development processes – may do the same. These ongoing changes severely restrict the design of tightly-coupled modeling environments.

The notion of multi-model ecologies seeks to address this by conceptualizing systems of interacting models and datasets in a manner that emphasizes their evolutionary nature and socio-technical context [1]. From this perspective, models are viewed not as isolated elements, but as potentially sociable individuals co-evolving with one another in a changing environment. As illustrated in Figure 1, models may interact in different ways – statically or dynamically, directly or indirectly – and multiple interaction pathways are possible. Compared with e.g. a middleware approach, the aim is not necessarily pure composability, but rather the cultivation of an evolving set of resources that – with some additional effort – can be configured and reconfigured for different purposes, and which also adapts to changing knowledge (needs).

One advantage of this approach is that possibilities for model integration and reuse are not dictated by top-down design, but emerge over time from ongoing development efforts. This has implications for the model development process: modelers should design and document models with an eye towards their potential reuse, and should deliberately seek opportunities to leverage the modeling work of others. A full set of guidelines regarding this concept is provided in [1].

3 The HUES Platform

The HUES platform comprises a set of tools to aid in the design and operation of district and urban energy systems. The platform has been developed over several years by multiple researchers at the Empa Laboratory for Building Science and Technology and the Chair of Building Physics at ETH Zurich. There are three core items around which the platform has grown:
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- The **Building**, the dynamic thermal simulation used to determine the energy demands of individual buildings, usually as an annual series of hourly values.

- The **Energy system**, the district-level system that meets demands by managing supplies through energy conversion and storage.

- An **Optimization suite**, consisting of a range of optimization algorithms (for example a multi-objective genetic algorithm) that can be applied to any variable or objective present in the platform.

In addition there are many smaller modules and datasets that perform specific functions. These include: (1) stochastic models that produce **use profiles** that represent time-varying occupant uses of buildings; (2) a **longwave radiation** script that couples multiple building models to allow radiation to be exchanged between them; (3) a statistical **microclimate emulator** that fits a model to the results of a **CFD** simulation, for example to represent urban air flow patterns; (4) **solar gains** calculations based on urban morphology; (5) a **network** model that links multiple **energy systems** together; (6) **configuration** scripts that are used by the **evaluation function** to allow the **optimization suite** to manipulate specific variables; (8) detailed simulations of **hydraulics** and **conversion / storage** processes; (9) implementations of **controllers** for the **building** and **energy system**, plus an embedded controller for real systems (allowing hardware-in-the-loop); (10) **GIS** and **BIM data** sources; and (11) **cost database** for economic optimisation.

Figure 2: Current composition of the HUES platform. White boxes are **datasets** and grey boxes are **modules**, with a darker shade indicating a more important item.

The platform was originally developed to allow an optimisation algorithm to address variables relating to both buildings and the energy system. This work is presented in [7], where a multi-objective genetic algorithm (NSGA-II) is used to run a building energy simulation (EnergyPlus), and the demands from this are passed to an energy system simulation (a mixed-integer
linear programme). Other parts of the platform have been developed through separate research, for example the stochastic behaviour models were used in [10], the microclimate emulator was developed for [9], and the longwave radiation exchange was an outcome of [8].

The recent initiation of several projects related to the HUES platform has raised new research questions and challenges. In seeking to guide the platform’s growth and development, a key question is how to facilitate the reuse and integration of the models and datasets within it. The foreseen expansion of the HUES platform – in terms of the range of research questions addressed, the number of involved researchers and the disciplinary scope – poses several challenges in terms of preserving and enhancing opportunities for model reuse and integration. In particular, as the number of models, datasets, and actors increase, ad-hoc methods of sharing model code, results and related knowledge will no longer suffice. This hinders opportunities for the reuse and integration of models and datasets, precisely when realization of these opportunities may be most beneficial.

4 The Role of Model Metadata

A key enabler of model reuse and integration is the ability to efficiently identify, evaluate and select potentially useful models and datasets. Missing from the existing repertoire of communication channels – e.g. model documentation, scientific publications, online code repositories – is a tool to facilitate: (1) the comprehensive and efficient identification, evaluation and selection of existing models and datasets, and (2) the sharing of newly developed models and datasets. The core of such a tool must be a method for sharing and navigating model metadata. If the code of a model is the “data”, model metadata in this case comprises essential information about the contents of this code to enable reuse.

Concepts of the semantic web can help to address this need. The semantic web is a movement aimed at converting the current Web from a “web of documents” into a “web of data”. The central idea of the semantic web is the structuring of data in the form of subject-predicate-object expressions – i.e. as a graph database – that enable targeted navigation between different pieces of data. For instance, data describing a particular model may be linked with data describing a dataset used by the model, which may in turn be linked with data describing the model that produced this dataset. These formalized relations can facilitate the efficient and effective navigation of large sets of model metadata.

Before model metadata can be structured and navigated, it must be made available. An issue here is the aforementioned evolutionary nature of multi-model ecologies. New models are constantly being developed and existing models improved, and old models become obsolete. Moreover, these changes are occurring in a distributed manner, with different researchers focusing on different elements of an ecology. Sharing of a distributed and constantly changing knowledge base may be effectively enabled via wikis as evidenced in particular by the success of Wikipedia. In serving as a platform for the ongoing collection of distributed information, wikis can be a useful channel for the sharing of model metadata in a multi-model ecology.

The semantic wiki concept combines the advantages of the semantic web in terms of structuring data with the advantages of wikis in terms of collecting distributed and ever-changing knowledge. A semantic wiki is essentially a wiki in which information is presented in the form of subject-predicate-object datapoints, allowing it to be described and navigated in a structured manner. Similar to XML, semantic wikis represent information in a format that is both

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1 A wiki is a website which allows for the collaborative editing of content.
human- and machine-readable\[2\]. Semantic wikis have been used to enable the distributed collection and structuring of knowledge on topics from global power production \[3, 2\] to building design/retrofit options \[10\].

5 Development of a Semantic Wiki for the HUES Platform

To enable the sharing and navigation of model metadata in the HUES platform, we have initiated the development of a semantic wiki. The first step has been to establish which types of model metadata need to be captured in the wiki, and how this information should be structured. In other words, we have sought to identify the relevant range of subject-predicate-object relations – the ontological structure of information in the wiki. This structure is illustrated in Figure 3.

![Figure 3: Current ontological structure of information in the wiki.](image)

The core of this ontological structure are the nodes “module” and “dataset”. Modules refer to pieces of executable computer code which in combination may comprise a complete model. Datasets refer to collections of data which may serve as inputs to, or represent the outputs of, modules. Datasets and modules are linked to a number of other datapoints. For the case of modules, this includes: a description of the module, the name of the file, a download URL, a documentation URL, the language in which the module is programmed, other modules called by this module\[3\], the author of the module, and any datasets which the module may draw from or output.

Additionally, the ontology includes the nodes “module class” and “dataset class” to categorize modules and datasets respectively. For instance, all energy hub models might be designated with a module class “energy hub models”, or all datasets pertaining to the village of Zernez, Switzerland, might be designated with a dataset class “Zernez case”. Modules and datasets may belong to multiple classes, and new classes may be continually defined by users as the platform evolves. The purpose of classes is to allow higher level groupings, which may aid modelers in identifying opportunities for model/dataset reuse and/or integration. For instance, certain sets of modules may together represent multiple perspectives on, or implementations of, a particular system. By assigning these modules to the same class, we facilitate researchers in using these resources to explore the consequences of different system representations.

\[2\]Semantic wikis often use the RDF data model, which can (but does not have to) be represented in XML syntax.

\[3\]Based on this, it is also possible – via a query in the wiki – to identify which other modules call this module.
In addition to modules, datasets and classes, we define a “collection” node. Collections refer to tailored groupings of modules and datasets, which may be run in combination for a specific purpose. An example of how collections may be used is provided in the following section. It is important to keep in mind that the structure illustrated in Figure 3 is neither definitive nor universally applicable. Based on the information needs or terminological preferences of the actors involved, new categories of metadata may be needed. The structure of the ontology may also change over time in line with the changing needs of these actors.

6 Implementation and Use of the Wiki

The ontological structure illustrated in Figure 3 has been implemented as a semantic wiki and populated with metadata pertaining to the modules and datasets of the HUES platform. The developed wiki makes use of MediaWiki – the wiki technology underlying Wikipedia – together with the Semantic MediaWiki Extension, which enables the structured representation of information in the wiki. Figure 4 shows several screenshots from the wiki.

By navigating the linked pages of the wiki, researchers can identify and evaluate possibilities for model reuse and integration. For instance, if Researcher X is looking for energy supply data to serve as input to an energy hub model, she might look at the list of dataset classes on the homepage of the wiki, and navigate from there to the “Energy hub supply data” dataset class. On this page, Researcher X can see a list of relevant datasets, with a short description of each. If Researcher X finds a useful dataset, she can simply navigate to the page for that dataset and click on the download URL to obtain it.

As another example, we take Researcher Y, who is just starting to develop a model for the purpose of identifying an optimal energy hub configuration for the Swiss village of Zernez. In order to accomplish this, Researcher Y needs, amongst others: datasets describing the building stock, weather and solar insolation in Zernez, an energy hub model and an optimization module. The first action Researcher Y might take in this case is to create a new collection called “Zernez energy hub optimization”. Starting from the wiki’s homepage, he might then navigate the wiki looking for potentially useful modules or datasets. Each time Researcher Y finds a useful module
or dataset, he adds it to the new collection page. When Researcher Y is finished, he simply clicks the “Download collection as ZIP” button at the bottom of the collection page, which automatically navigates to the download URLs of the relevant modules, compiles them into a ZIP and saves them to Researcher Y’s computer. Researcher Y may not yet have a complete executable model, but he has a strong starting point that makes efficient use of the formalized knowledge already present within the platform.

Researcher X and Researcher Y will not simply use the models, but will add to and improve them for their particular purpose. When they have finished constructing their models, they may create new pages on the wiki describing the modules and datasets they have developed. This allows future researchers to benefit from their work in the same manner that they benefited from the work of others. Furthermore, in creating a new collection on the wiki, Researcher Y has left behind a resource that may be used by other researchers seeking to develop models for similar purposes. By viewing the list of modules and datasets that Researcher Y has used in constructing his model, future researchers may be guided in constructing their own models.

7 Role of the Wiki in the Future Development of the Platform

In further developing the HUES platform, we intend to combine the different facets of existing work in new ways, to address new research questions that have arisen. For instance, it is important to understand the degree to which uncertainty regarding time-varying loads affects energy system design decisions. The multi-level optimisation process will be combined with the stochastic models to investigate this. Next to this, urban areas have many physical processes that affect energy use in buildings that are currently omitted when analysing prospective urban configurations. The optimisation suite will be re-purposed to explore arrangements that account for the urban microclimates that they produce, requiring the solar gain analysis, longwave radiation coupling and microclimate emulator to be linked. Additionally, tightly integrating the control of buildings and district-level energy systems may give significant benefits, for example allowing buildings to be pre-heated when waste energy is available from another building. Currently there is no easy way to simulate this process, so the building and system controllers will be linked to their respective models and to each other.

Achieving these advances with disparate simulation tools, or attempting to build a new tool to address all issues involved directly, would be an infeasible amount of work. With the flexibility of the HUES platform, this becomes manageable (though still not trivial, since modules must be adjusted and new functionality added). The insight provided by the wiki assists in this process, allowing many people to collaborate on such improvements.

The example use cases described in the previous section represent two of many possible scenarios for the use of the wiki. The representation of model metadata in the form of a semantic wiki offers many possibilities beyond those described above. For instance, it is possible to incorporate automatically generated and interactive visualizations of the simulation platform’s structure based on the model metadata in the wiki. These visualizations would provide an up-to-date overview of the platform structure, enabling modelers and stakeholders to keep pace with developments and the platform’s cultivators to track progress.

In the longer term, we foresee the potential for the wiki to facilitate comprehensive exploration of model input and output data. An advantage of semantic wiki technology is the hosting, analysis and visualization of linked data – collections of structured data spanning multiple data sources. This can enable the comprehensive exploration of data across different models, opening
up possibilities to better understand the effects of different assumptions or perspectives applied to the same problem. Used in this manner, the wiki can serve not only as a resource for model development, but also a platform for stakeholders and researchers to interactively explore model results and the data underlying them.

Progress along these lines is not without challenges, including: (1) motivating contribution to the platform, (2) ensuring the usefulness and comprehensibility of the wiki as a portal to the HUES platform, (3) dealing with intellectual property, and (4) communication of (the bounds of) model validity. To address the first of these issues, we are developing software to partially automate the process of populating the wiki with model metadata. To address the second, we are working with model developers towards a shared definition of the wiki ontology. To address the third, we are designing mechanisms to share model licensing and terms of use information via the wiki, and ways to selectively restrict access to certain portions of the wiki – allowing researchers to individually tailor the sharing of their modules by choosing amongst different possible licenses (e.g. GNU GPL, CC BY-NC-SA). To address the fourth, we aim to develop a set of documentation guidelines to ensure that evidence of a model’s demonstrated scope of validity is effectively communicated to users via the wiki.

Next to these challenges are the very practical issues associated with enabling software-level interaction between modules. In line with the multi-model ecologies approach, our aim is not pure composability – strict plug-and-play capability of components. Rather, it is the cultivation of a evolving set of resources whose components can, with some additional effort, be combined and recombined in different ways for different purposes. Instead of constraining model development with a strict set of guidelines to ensure software interoperability, we leave it to researchers themselves to develop and manage the interactions between different modules as necessary. Via the wiki, we seek to ensure that the developed linkages between these modules – whether in the form of ad-hoc computer scripts or more comprehensive middleware applications – are preserved and made available for use by others. In this manner, possibilities for model integration grow over time, as the platform itself grows.

8 Conclusions

Realization of opportunities for model reuse and integration is essential to furthering the study of complex urban systems, and many challenges remain. This paper has sought to address a key one of these challenges – the need for sharing model metadata. To this end, we have described the preliminary development of the HUES platform and an associated semantic wiki. We have described the ontological structure of this wiki, several use scenarios and possible future developments. As the HUES platform grows, the wiki will ensure that the platform develops as a coherent system rather than a disparate set of isolated tools.

It is in the nature of complex systems that no single formalism can sufficiently describe them [15]. In seeking to enhance our ability to grasp complex systems of different types, it is essential that we employ a range of tools reflecting different formalisms. It is only in integrating these tools that we can overcome the limitations of our bounded rationality as researchers. By enabling the sharing and efficient navigation of model metadata, semantic wikis can facilitate such integration, and help us to deal more effectively with complex systems.

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