Balancing demand and supply: Linking neighborhood-level building load calculations with detailed district energy network analysis models

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ABSTRACT

Operational building energy has long been recognized as both a major contributor of as well as an opportunity to save carbon emissions. To do so, one may follow two paths, reduce the energy use in buildings (demand) or provide the required energy in more efficient ways (supply). In the literature, extensive research has been made on both fronts and at different levels of detail resulting in a myriad of tools unique to specific stages in the development timeframe of a district energy project. This manuscript describes a modeling workflow based on a new Rhinoceros-based plugin that combines an Urban Building Energy Model with a network topology optimization and a heat generation scenario model bridging the gap between the planning phase and the design phase. The new plugin builds on the foundation of uml, a Rhino-based link to Radiance and EnergyPlus developed at the MIT Sustainable Design Lab, as an addition to the demand simulation module. A demonstration project shows how the workflow serves as a stepping stone from the design environment of Rhinoceros to the technical environment of TRNSYS, thus enabling a more streamlined process to use different modeling strategies for different purposes, within the same design workflow.

1. Introduction

The world’s population is becoming increasingly urban, meaning that cities need new buildings and infrastructure to accommodate a growing population including newcomers for the surrounding countryside [1]. Unfortunately, due to either a lack of space or the absence of policies that promote urban density, new urban developments are often relegated to the urban periphery where they contribute to urban sprawl. Another reason for growing urban resource consumption can be traced back to increasing standards of living which have been associated with increased use of air conditioning systems and other amenities [2]. These trends go against sustainability principles which call for decreasing resources consumption while achieving more welfare gains [3]. If energy can be considered to be an economic “good” linked to living standards, there is a need to “make more and better with less” of that energy, especially when considering the environmental impact of energy production. District energy systems (DES) are considered a key element in the transition to sustainable energy [4]. They have offered a promising way to reduce the emissions by exploiting synergies with other societal activities. Historically, heat resources have been in the form of Combined Heating and Power (CHP), Waste-to-Energy (WtE) or industrial processes. However, more recently, renewables have been introduced into DES to lower overall environmental impacts [5]. DES require a certain built density and mixed of programmatic building use to reach their full potential. Better urban planning is therefore one of the requirements for creating suitable boundary conditions for DES. There is hence a need for planning tools that can be easily integrated into current design practice. The methodology presented in this paper specifically addresses the interface between urban planning and energy supply systems development by offering a balanced workflow that allows urban planning teams to effectively collaborate with their consultants during the development of district heating (DH) networks in the context of urban planning.
projects. Similar workflows have been presented in the past. Indeed, Fig. 1.1 shows there is a plethora of modeling approaches available that each require design teams to repeatedly provide different information at the similar design stages of a product. An improved approach would allow all parties to work on the same data. Due to recent development of simulation workflows that link urban massing models of so-called urban building energy simulations (UBEM) [6], estimates of building load profiles for heating, cooling and electricity can nowadays be generated from the Pre-feasibility study phase onwards. This is the point when real synergies can be identified between those load schedules and potential energy supply systems.

What specific questions can be asked at this point? It is well known in the field of district energy that the linear heat density, which is defined as the annual delivered heat per unit of length of distribution network, is an indicator of the viability of a network. Unfortunately, estimating the linear heat density before district heating is established in a city or neighborhood is especially challenging. Without empirical data, it becomes very hard to make the case for district energy solutions in future (re)development projects. This viability comes down to two components: (i) the competitiveness of centralized heat supply versus decentralized heat supply and (ii) the heat distribution cost. To solve the heat distribution cost portion of the problem, U. Persson and S. Werner [8] proposed the concept of effective thermal width, which helps to reduce the required empirical parameters in the distribution cost equation down to one: the concept of thermal width, w. Thermal width is defined as the ratio of land area and total route length of a district energy network across this area. It is a performance indicator for how effective a given area is covered by a district energy network with smaller numbers corresponding to more desirable conditions: high dense inner cities can be found in the range 50 < w < 60 meters [9]. As the authors have shown, one can develop an empirical equation which, when combined with the known Floor to Area ratio (or the Plot Ratio) of a site, yields the site’s thermal width and thus the heat density. Unfortunately, this empirical equation is unique to a particular region’s heat generation and construction economics. In other regions with limited district energy experience, planners therefore have no other choice but to estimate the length of the network to calculate the linear heat density and assess the advantage of district heating versus decentralized solutions. This can be a challenging task, especially for projects in their early development stages when the focus of decision makers lies on defining programmatic needs profitability and overall site massing.

To encourage the development of so-called “4th generation” DES, a new “technological and institutional concept for sustainable energy systems” [10], this paper proposes a workflow developed around an existing urban planning tool that supports the simulation potential of district heating scenarios at an early stage. The system is complementary in depth and rigor to the aggregated load curve resulting from the earlier mentioned UBEM methods. With this method, the linear heat density becomes endogenous to the model as the required thermo-physical properties of the distribution network are rendered inside the model. The workflow goes as follows: Building heat loads are calculated via the Autozoner approach developed by Dogan et al. which abstracts urban massings into a linear superposition of two-zone shoebox models in EnergyPlus [11]. The network topology is derived from a simple optimization algorithm that yields a revenue-optimized solution; Various thermal plant heat generation schemes are then simulated using a simple steady-state model. Finally, a full-size dynamic model is automatically generated for the TRNSYS software environment to help transition towards a more detailed analysis.

This workflow was developed within the Rhinoceros environment [12], a popular Computer-Aided Design (CAD) software that is widely used in leading architecture and urban design schools and practices worldwide. Since an architectural massing model, including street grids, and a district energy system are geometrically similar—assuming that trenched-pipe layouts are generally located below streets—energy supply and demand estimates can largely be based on the same dataset, reducing the earlier mentioned need for planning teams to enter the same data several times or to maintain synchronized datasets. The resulting workflow is compatible with an integrated and iterative design process. Moreover, as will be shown below, architectural design decisions can be influenced positively via early feedback provided by the DES analysis.

2. Review of district energy models

District Energy Models are an interpretation of the problem domain framed by Urban Energy Systems Models (UESM). An UESM
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