Designing and Evaluating District Heating Networks with Simulation Based Urban Planning

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Abstract

The integration of energy and indoor comfort aspects into the early stage of urban planning is essential to conceive energy efficient urban structures and to avoid expensive compensation measures in the later building design. This could end up with increased insulation levels, complex air conditioning systems as well as increased energy demand during the building usage or inefficient energy supply concepts. Besides indoor comfort and the energy demand for heating, cooling, ventilation and daylight, energy supply options based on district heating (or cooling), have to be considered in an early stage of design as they may constitute highly efficient alternatives with respect to building specific heating units. Incidentally, this sub-project is part of the project titled Collaborative Design Platform (CDP) which is a computer based real time tool for urban development in early stages of design decision making. Referring to a subproject intending to integrate different energy aspects into the CDP, the paper concentrates on district heating networks (DHN). The objective of this study is to evaluate the possibilities of implementing a new plug-in in the early stage of urban development in order to design and evaluate the adequacy of district heating networks.

1 Introduction

In recent decades, District Heating Networks have found large improvements both in practice and modeling. The main advantages of district heating networks are the reduction of pollutant and thermal emissions in the city area as well as increasing the safety, due to the absence of combustion systems at the final users of thermal energy. For the same reason also the transportation of fuel in the city area can be significantly reduced by the use of district heating networks. In this scenario, the district heating allows to achieve high conversion efficiencies by centralizing in few large power plants the need of thermal energy in household sector (Ancona, Bianchi, Branchini, & Melino, 2014). In order to improve the operation of district heating systems, it is necessary for the energy companies to have reliable optimization routines, both computerized and manual, implemented in their organizations. However, before a development plan for the heat-producing units can be constructed, a prediction of the heat demand first needs to be determined (Dotzauer, 2002). This fact is also necessary in the early stages of urban planning where the rough idea of street networks, accessibilities and building massing are sketched, however in that scale it is not easy to find a tool which is able to simulate and give feedback in real time to iterate several alternatives through the urban design and planning decision making processes.

It is already being proved that the simulation of the urban models including the district heating network (DHN) system is possible to be coupled with an optimization algorithm in order to illustrate the potential of such an approach for determining the optimal solution or a set of near-optimal solutions for a very complex system synthesis and design (Curti, von Spakovsky, & Favrat, 2000). Nevertheless, extending the idea of optimization and decision making methods into early stages of urban design needs more exploration. One of the recent developments that enables the possibility of iterative decision making is Collaborative Design Platform (CDP). CDP as a computer based real time simulation and visualization tool is developed for urban planning in the early stages of design decision making which gives the opportunity as a flexible platform to include simulation and analysis add-ons with different objectives. The following section is going to discuss the concept of CDP in more depth and detail.

2 Background Collaborative Design Platform (CDP)

By the advent of computer simulation tools into architecture and urban design professions, most of the contributions in recent years devoted to modeling, drafting and managing of design solution mainly at the end of the planning process. The CDP project has started with the idea of coupling physical and digital contexts in early stages of urban design to be able to run real time analysis to get feedback on design and planning proposals (Schubert, 2014). The concept is an interactive table with a touch screen to load the urban data regarding buildings, routes and infrastructures within the boundaries of the design location. The platform enables its user to run real time simulations for physical models within an interactive and communicative interface. The framework focuses on establishing a tool with an interactive interface for collaborative design thinking in order to investigate digital methods that can be transferred to conceptual planning (Schubert, Riedel, & Petzold, 2013). This approach enables visualization of planning decisions in early phases to be discussed and shared between citizens, stakeholders and other planner in a collaborative milieu.

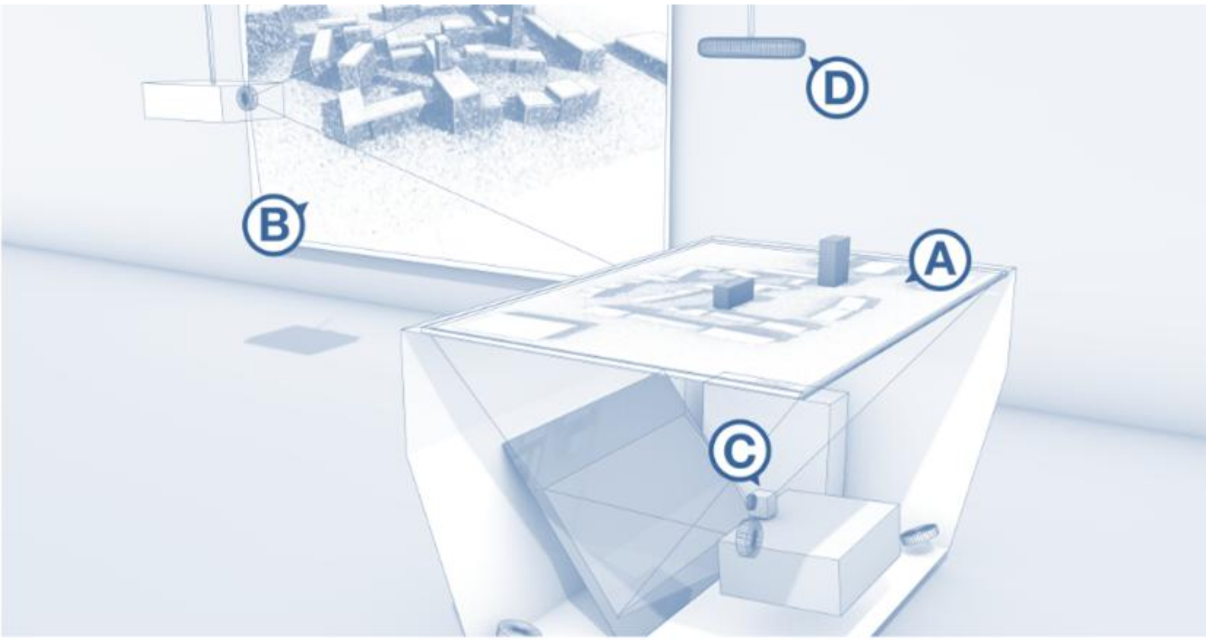


Figure 1: Hardware concept: Multi touch table in combination with Microsoft Kinect 3D camera and additional perspective display

CDP table consists of hardware and software concept of the prototype. The hardware setup (Fig. 1) is based on a custom-made, large-format multi-touch table. This is the work surface and design platform for the architect (A). The underlying plan information is derived from GIS data in City GML format, which is displayed as figure ground on the surface of the multi-touch table. A perspective view (B) of the entire scene is displayed on a separate, vertically mounted touch screen that accepts touch input. The camera (C) captures an impression of the “footprint” of the placed objects (position, size, angle, shape), anchors these in the coordinate system and makes it possible to track the movement of objects as well as fingers. An additional IR depth cam-era (D) mounted above the multi-touch table captures the real 3D geometry model of the objects placed on the table. Each distinct element of the footprint is registered and allocated an ID, which can then be linked directly with the digitized 3D form obtained from the IR camera. This combination makes it possible for the user to shift or turn registered objects without its 3D form to be recognized and computed in real time. Every change to the real model – whether a block is modified, shifted, removed or a new object is placed on the table's surface has a direct real-time impact on the digital image, as well as the calculations, the perspective view and the virtual sketch. The CDP (Fig. 2), with the concept of combining physical and digital models to be coupled with real time analysis has several challenges into diverse directions and scales. Starting from the requirements of architectural and urban planning processes following key points could be addressed:

Figure 2: CDP // Collaborative Design Platform

2.1 *Creative thinking and decision making*

Quick spread of digital tools in architecture and urban design professions has limited the potential of these tools to be embedded into the design process. Mainly, the common application of design and planning tools is restricted to end process evaluations. However sometimes it is possible that computers give new ideas to the designer by spontaneous actions, but the main guider is the architect to choose between the alternatives. We cannot expect computers as creative as human because, the human itself have made computers exist but there can be a collaborative process between human and computer. The computer enables imagination transferred to build environment.

A collaborative design process requires tools to transform the linearity of such an approach into iteration oriented and feedback based loops. In that way, the end point outcome can be improved integrating real time feedbacks and solutions. The CDP aims to bridge this gap by pushing back the mutual discussion into early stages of design through the introduction of a circular decision supported thinking process.

2.2 *Variety of applicable plug-ins*

Each design task or design approach based on the complexity of task and key features requires a certain set of tools to justify decisions. This means that the parameters and analysis to be checked in different projects could vary based on the design question that is going to be answered by any set of tools. Within the last two years, the CDP has built a large number of plug-ins for different simulation and analysis purposes. The most significant developments are: shadow and radiation analysis, 2D wind simulations, coupled mixed and augmented reality, real time sketching etc (Schubert, 2012). Within the process of development, the recent idea focuses mainly on energy performance analysis on city and neighborhood scale. In this regard, the question of designing district heating networks and evaluating their viability in early planning level is considerable. This paper includes recent achievements to implement this concept into the CDP platform.

3 Plug-in for District heating network

District heating offers a set of benefits compared to building specific heating plants concerning energy efficiency (high efficiency of the central heating plant, optimal design specific to base, medium and peak loads), possibility to use large scale renewable energy resources (waste heat, deep geothermal energy, etc.) as well as a higher degree of flexibility. However it requires a sufficient density of heat demand to ensure a cost and energy efficient operation (limiting heat losses in the grid). The higher the heat demand of the supplied buildings in relation to the grid length, the more efficiently and economically a heating network can be operated (Lund, Möller, Mathiesen, & Dyrelund, 2010).

Besides the construction standards of the buildings, depending to a high degree on their construction period, the parameters defined in the urban planning process, such as building orientation, form and shapes, distance between buildings, height of the buildings and building usage have a significant influence on the heat demand of the buildings and thus on the density of heat demand.

Within this regard, the goal of this project was to define a method and to implement it in the CDP in order to design and optimize the grid of district heating networks, evaluate the heat demand related to the length of the grid and thus give a first evaluation of its economic feasibility. This should permit to analyze the influence of the urban design and structure on the district heating supply options in the early urban planning stages. For that, the following aspects had to be integrated in the Collaborative Design Platform (CDP):

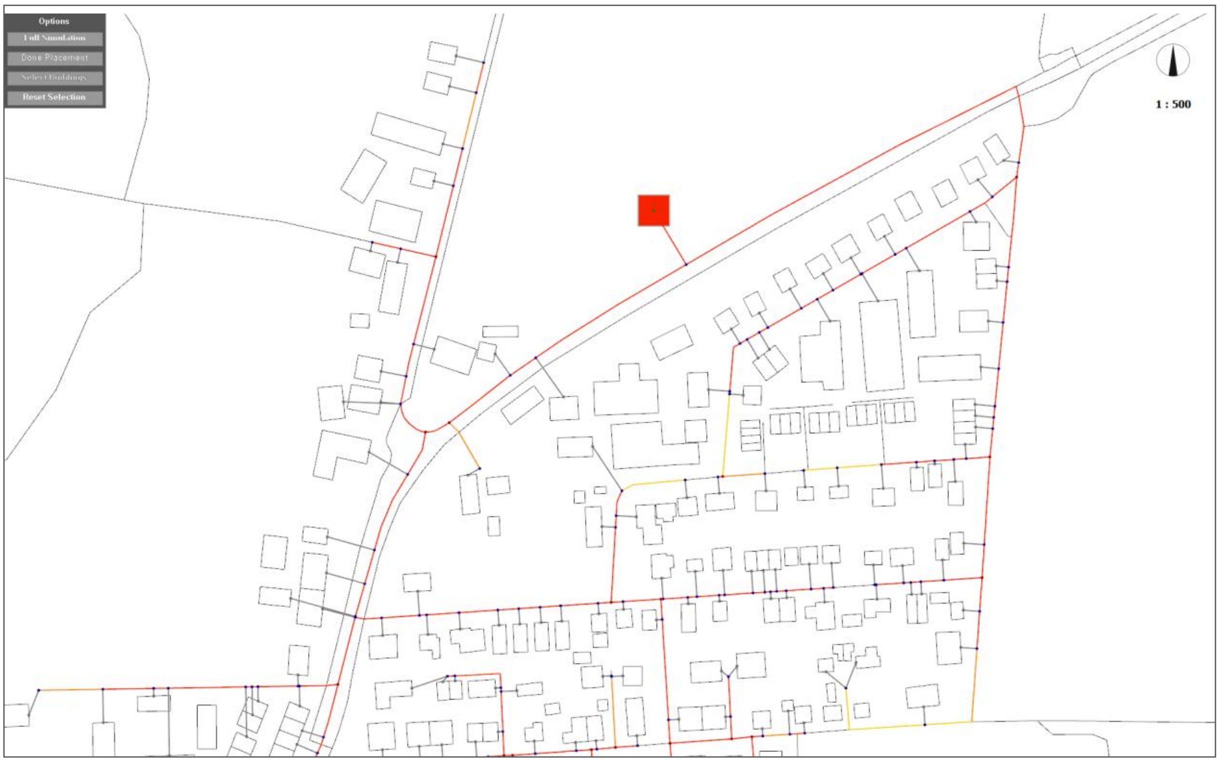
- Optimal grid generation for heating networks
- Positioning of the heat plant (manually / automatic optimization)
- Determination of the heat demand of the individual buildings in the considered area
- Calculation of the heat demand per meter grid (specific to each section) and graphical representation for first feasibility evaluation

4 Calculation of the of heat demand per building

In view of the calculation of the heat demand per meter grid, the demand of the individual buildings in the design area for heating and domestic hot water is determined in a first step. This is done by applying a simplified method based on statistical data-specific heat demand values depending, for residential buildings, on the building usage, type and construction period (Wohngebäudetypologie, 2015). For non-residential buildings the specific values are only dependent on the building use (Staatsministerium, 2011). The method thus does not consider the exact building form, but it is based on the energy reference area of the building (habitable / useful area). Industrial buildings are not considered due to their very individual requirements.

For a first rough estimation of the economic feasibility of heating networks, as intended in this project, this method is considered as sufficiently accurate. However, it requires an extensive database with detailed information about the buildings (usage, type of building, construction period, habitable / useful area, etc.). In case such an accurate data base is not or just partly available, the required information can be accessed through an on-site survey of the buildings in the study area, and implemented in the digital database (GIS).

Since the heat demand for each building is independent from outside parameters (other buildings, position, orientation, etc.), the computation can be performed in parallel. When a new building is added to the design area, or one of the dependent parameter for the heat demand is changed, it has its requirement (re-)calculated, before (re-)introducing the building to the grid. The evaluations are then directly stored in the instances of the data structure for buildings in the CDP Framework. Figure 3 shows screen shot of the CDP display with district heating network connecting buildings to the power plant.



	Yearly heating demand per meter [kWh/Trm.a]	RGB Color Values
	< 500	R: 245 // G: 245 // B: 0
	500 - 1000	R: 245 // G: 210 // B: 0
	1000 - 1500	R: 245 // G: 140 // B: 0
	1500 - 2000	R: 245 // G: 070 // B: 0
	> 2000	R: 245 // G: 035 // B: 0

Figure 3: Evaluation of heating network

5 Network Generation and positioning of the heat plant

Due to the complexity of heating networks, a few assumptions and simplifications were made. This greatly assisted in the automation of the network creation. The following limitations were imposed:

- The network does not contain any closed circuits (star like network).
- Only preferred buildings are connected to the network.
- The network can run only under streets. Exception is the connection between buildings and the rest of the network.
- Buildings are connected with the network through the middle point of the nearest façade to the network.
- The heating plant is connected on a similar principal as other buildings.

Based on these rules, an initial undirected graph is created matching the structure of all roads. Afterwards, all buildings are simultaneously connected to the graph, as described in the rules. Taking into consideration where the heat plant is placed, the Dijkstra Algorithm for the single-source shortest path problem is applied (Dijkstra, 1959). Utilizing the generated paths from the algorithm transforms the graph to a Minimum Spanning Tree (MST) (Cormen, Leserson, Rivest, & Stein, 2001). Such a tree contains all points connected with those edges, with a minimal total distance and without cycles.

Based on this approach two different methods, depending on the positioning of the heat plant, are conceptualized and developed. The concept of optimizing DHN is based on 2 different choices, first way is to place the power plant manually by the user, second is based on finding optimum location for the power plant to be places.

5.1 Selective position based on user input

The core of the method validation and evaluation of the network is based on a heat network, whose plant is placed by the user. The location, size and orientation of the heat plant is defined through a physical object that the users places on the surface of the table. Based on the definition of the plant the network is constructed and analyzed in real time (Figure 3). Based on the principles of CDP the power plant or energy source could be modified and placed in different location and at the same time real time calculations visualized on the table surface to find best possible location for the planning scenario.

5.2 Automatic position evaluation

On this method, the designing context is discretized using a Quadtree structure (Finkel & Bentley, 1974). For each cell of the Quadtree a heat plant is placed in the centre of it. From there the base approach is applied to generate a heat network. Each network is evaluated based on the total distance and heat distribution of the segments of the network and a color value is then associated based on the worst and best performing networks (Figure 4). Since the generation and evaluation of each Quadtree cell is independent of all other cells, each cell evaluation is run in parallel.

The algorithm starts at the first level of the Quadtree, where only one cell, that's the size of the whole design space, is created and evaluated. Each cell from the next level of the Quadtree starts only when all cells from the previous level are complete. Since each cell of a finer level is contained within a coarser one, it is possible for the heat plant in both to connect to the same segment and only the distance between the plant and the segment to be the difference between the generated networks. For this reason a list of all previously generated networks is stored during the algorithm runtime. Every time a plant is placed, the algorithm checks if there was a similar network already generated. In that case it directly uses the stored information and modifies only the distance between the plant and the rest of the network. If there is no similar network, a new one is generated and stored in the list.

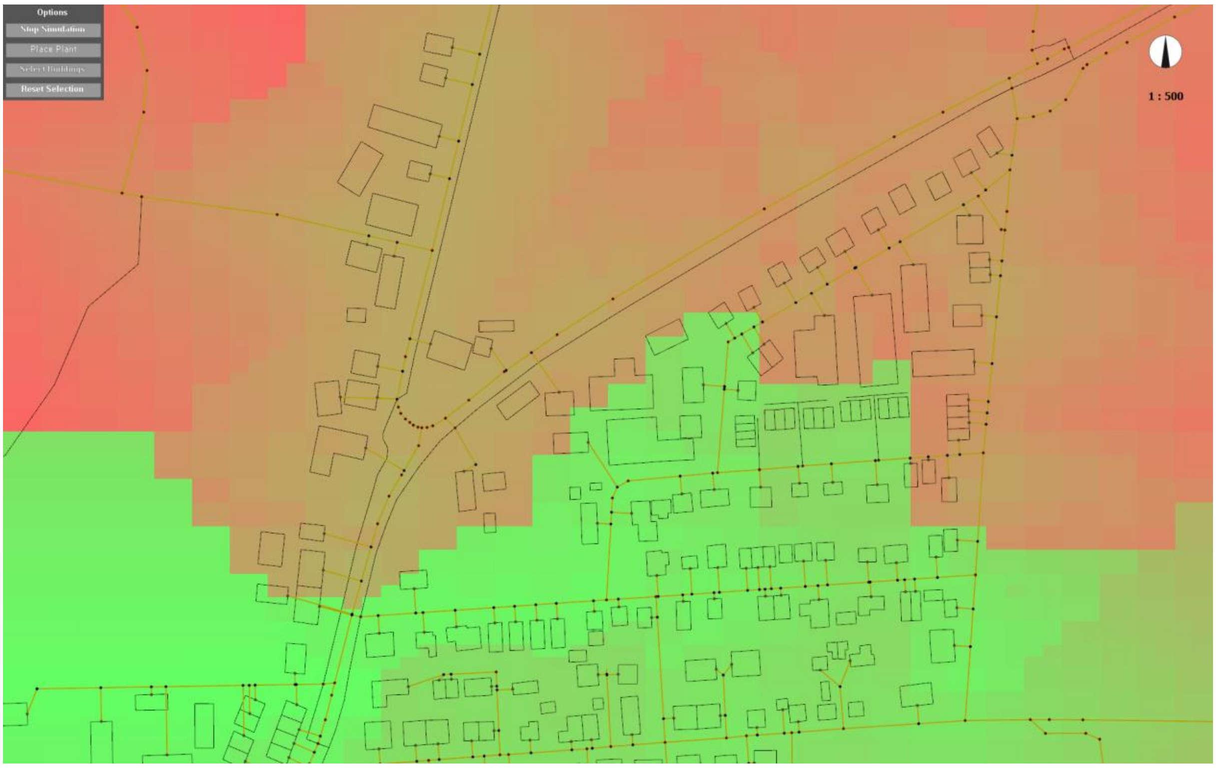


Figure 4: Evaluation of several heating systems simultaneously

6 Computation of the heat demand per meter grid

The heat demand per meter grid is determined for each grid segment by asserting how much heat passes through it. This is computed by adding the heat demand of all buildings that pass through it divided by its length. It is then represented in the CDP according to a fixed colored scale (see Fig. 3). In that way, it is possible to evaluate if some parts of the study area should not be connected to the network because of too low demand density. The value of 500 kWh per year and trace meter [kWh/Trm.a], as defined by the KfW subsidy program for renewable energy "Erneuerbare Energie Premium" [KfW], is often used in Germany as a threshold for economic feasibility. For that, heat losses in the grid are not considered. Only the main trace is taken into account in the calculation, not the individual house connections.

In order to test the accuracy of the developed method, a comparison could be realized for a district in which real heat consumption values are available. To evaluate the accuracy of the developed plug-in, the designed heating network can later be compared to an existing heating network. Figure 5 summarizes the overall procedure of DHN calculation through CDP development.

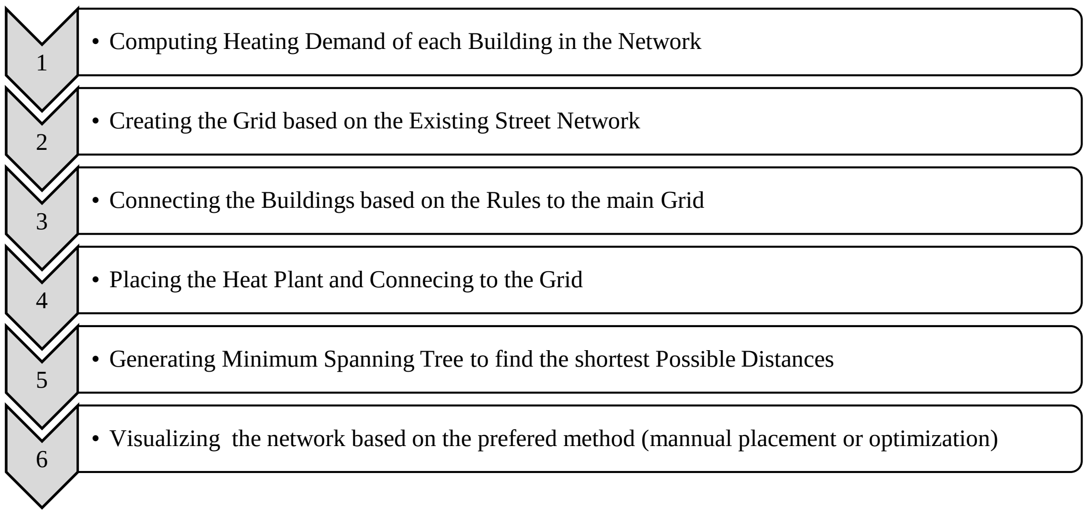


Figure 5: overall process of DHN integration with CDP

7 Summary

Over the framework of the project, integrating DHN to CDP, an interactive simulation for heating network optimization and creation was designed and implemented on top of the Collaborative Design Platform. The simulation computes based on easily extendable rules the heat demand for buildings in the area and with the computed information creates heating networks based on the position of the plant. The approach offers two options for the user in order to place the plant in the desired design context. The automatic position evaluation creates a "heat map" of all available positions and how they compare to one another. Based on this process the user has the chance to use physical boxes to place on the surface of the CDP and compare the actual networks. The implementation as a reactive simulation expands the use of the CDP and enables laymen (such as stackers, authorities, etc.) to be directly involved in the planning process, taking into account objective criteria through the decision making progression.

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