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HOLISTIC OPTIMIZATION OF URBAN MORPHOLOGY AND DISTRICT ENERGY SYSTEMS

C. Waibel[1, 2]*, R. Evins[1, 2], J. Carmeliet[2, 3]

[1] Laboratory for Urban Energy Systems, Empa, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland

[2] Chair of Building Physics, ETHZ, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

[3] Laboratory for Multiscale Studies in Building Physics, Empa, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland

*Corresponding author; e-mail: christoph.waibel@empa.ch

Abstract

This study presents a new optimization framework of both urban morphology as well as district energy systems. It is entirely embedded within the 3D-CAD software Rhinoceros / Grasshopper. Here, Mixed Integer Linear Programming (MILP) and Simulated Annealing (SA) are applied to solve the design and operation of a district energy system (DES) as well as the geometric design of the urban morphology.

Two approaches are compared: In the first, urban morphology is optimized using SA, and subsequently the DES for the final urban morphology is optimized using MILP. In the second approach, the district energy system optimization using MILP is nested within the urban morphology optimization using SA. Therefore, the higher level optimizer (SA) can exploit information from the lower level optimizer (MILP) and hence find better solutions. Results show that rather than addressing urban morphology and DES consecutively, both levels should be evaluated interdependently – especially for high carbon reduction targets. It is shown that urban planning should integrate both energy systems and morphology into a holistic design process.

Keywords:

Energy Hub; Urban Morphology; Optimization; District Energy Systems

1 INTRODUCTION

Increasing urbanization and population growth will increase the need for new urban development, especially in emerging cities. There is a huge potential in climate change mitigation and adaptation by designing these new urban districts to be energy efficient. This includes reducing energy demand for space conditioning and lighting by applying passive building and urban design strategies, including careful optimization of glazing ratios, building shape and configuration, natural ventilation and overshadowing. Also, the potentials for harvesting electricity with building-integrated photovoltaics can be increased depending on the urban morphology [1].

Finally, an important aspect to reducing overall lifetime cost and emissions is the appropriate selection and sizing of district and building energy systems which include technologies such as combined heat and power (CHP) and borehole thermal energy storage, etc. [2]. For this the “energy hub” model [3] can be used to size the components as well as solve the operational optimization to balance demands and supplies for every time step.

Previous studies have dealt with the optimal design and operation of each of the above mentioned categories independently, where building/urban energy demands are assumed to be fixed inputs for the optimization of energy systems [4]. However, the question arises if there exist interdependencies which, when considered simultaneously, lead to significantly different optimal design solutions.

The issue of interdependencies between building design and energy system design and operation has been studied in [5], where a multilevel optimization framework was developed and applied to an office building case study. Here, building design focussed on fabric construction properties, such as glazing ratio and insulation thickness. It was shown that this approach can exploit synergies between building and systems level.

2 METHODOLOGY

In this study a holistic optimization framework of both urban morphology as well as district energy systems (DES) is presented. A new optimization framework entirely within the 3D-CAD software Rhinoceros / Grasshopper has been developed, where Mixed Integer Linear Programming (MILP) and Simulated Annealing (SA) are applied to solve the design and operation of a DES as well as the geometric design of the urban morphology.

2.1 Geometric Optimization

SA is a metaheuristic optimization method developed by Kirkpatrick [7] inspired by the cooling process of liquid metal atoms. As SA solver, the native Grasshopper component Galapagos is used. The objective for the SA is to maximize profits for the developers of the new urban configuration:

$$Max\ Profit = P_{rent} - C_{DES} \quad (1)$$

P_{rent} describes the annual revenues from rent. C_{DES} is the total cost for the district energy system including operation. The calculation method for C_{DES} varies between the consecutive and the nested approaches and is explained in the next section.

The objective function value is not necessarily accurate, but serves as an incentive for the optimization process to increase total area of the neighbourhood. Increasing urban density and counteracting urban sprawl is also an intended development for reducing overall emissions [8].

2.2 Consecutive and Nested Optimization

Two different approaches are compared:

- Consecutive optimization of urban morphology then district energy systems
- Nested optimization of district energy systems as part of the urban morphology optimization.

Consecutive Optimization

The consecutive approach (shown in Fig. 1, left) has two distinct optimization stages. In the first stage the SA is optimizing the geometry of the urban morphology. After the SA terminates, the final solution is used as input in the second stage for the DES optimization.

During the first stage the operational component of C_{DES} is evaluated using idealized energy demands for space heating, cooling and lighting (see chapter 3). For the second stage, C_{DES} is re-evaluated for different carbon targets (but for the same final urban morphology) using the energy hub model, described in chapter 3.

Nested Optimization

The algorithm for the nested approach is shown in Fig. 1, right. Here, the SA again decides on the geometry of the urban morphology. The geometrical configuration is evaluated for energy demands using EnergyPlus and for solar potentials on the facades and the roofs using a custom model (see section 2.4). The demands and potentials serve as inputs for the energy hub model, which calculates C_{DES} subject to a pre-set carbon target. The entire nested optimization process is repeated for different carbon targets.

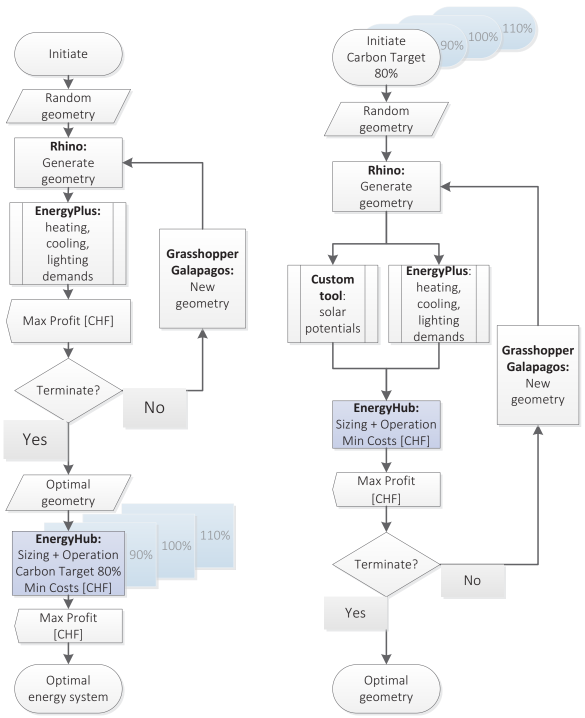

Fig. 1: Consecutive (left) and nested (right) optimization.

2.3 Demand Model

EnergyPlus is applied via the Grasshopper plug-in ArchSim [9] to simulate ideal hourly heating, cooling and lighting energy demand. The energy demands of all buildings and zones are aggregated. Cooling demands are converted to electricity demands.

2.4 Solar Potentials Model

Hourly annual solar potential profiles for each building façade and roof are obtained with a custom model fully implemented in Rhino Grasshopper ([Online] Available: https://hues.empa.ch/). This model factorizes both direct normal radiation and diffuse horizontal radiation from a weather file using detailed obstruction calculations of mesh surfaces for three distinct days of the year – summer solstice, winter solstice and equinox – using backward

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ray-tracing and then interpolates these obstruction levels for the remaining days of the year.

The advantage of such an approach is higher resolution geometric information of meshed surfaces, especially important in complex urban situations. Computing times are very low (In this work about 2.5 seconds for annual hourly solar profiles for all four buildings with four façades and one roof respectively, each surface discretised into a 10x10 Mesh, on a Win7 Intel Xeon E5-2643 3.30 GHz).

2.5 Energy Hub Model

The energy hub concept describes a modelling and optimization framework for multicarrier energy systems, where different energy carriers, conversion and storage technologies can be combined for flexible operation, thus enabling energy, cost and emissions savings [3].

In this study, the energy hub model is implemented as a custom Rhino Grasshopper component, since using Rhino facilitates both the geometrical design of urban morphologies, as well as building energy simulations.

The energy hub component is based on a generic VB.Net implementation ([Online] Available: https://hues.empa.ch/) and uses IBM ILOG CPlex as solver. It takes hourly energy demands and hourly solar potentials from all building facades and roofs as input. The carbon reduction target in % to a reference value can be pre-set, which then acts as an equality constraint during the optimization. The energy hub component formulates a Mixed Integer Linear Programming (MILP) problem to solve system sizing and operation variables of the DES.

The objective is to minimize cost in CHF, where the costs consist of annual fuel cost (C_{fuel}), annual cost for electricity purchased from the grid (C_{elec}), annual operational and maintenance cost for the systems (C_{om}), capital and installation cost for the systems ($C_{capital}$) annualized over each technology´s lifetime with an interest rate of 8%, minus the annual revenues from selling electricity to the grid (C_{sell}):

$$Min\ C_{fuel} + C_{elec} + C_{om} + C_{capital} - C_{sell} \qquad (1)$$

Constraints in the MILP are formulated for energy balance (demand equals supply), carbon target to a reference value (carbon offset for feed-in electricity is allowed), solar availability, façade / roof area availability, and technology performance (e.g. maximum charging rate or minimum state of charge for storages and minimum load for combined heat and power).

For computational reasons, the annual hourly demands and solar potentials, each consisting of 8760 values for each hour of the year, are averaged to 288 hours to represent one day for each month of the year. A drawback of using only 288 hours as 12 representative days for the year is that no long-term seasonal storages can be considered. The disadvantage with averaging data is the loss of information for typical profiles. However, since the schedules for internal gains are identical for all zones and buildings (no stochastic profiles), averaging data is acceptable since typical days would create unrealistic high peaks.

3 CASE STUDY

A case study is used concerning a new development consisting of four office buildings on a site in the city of Zurich (corner of Wilhelmstrasse and Limmatstrasse), measuring 81 x 81 m at its perimeter.

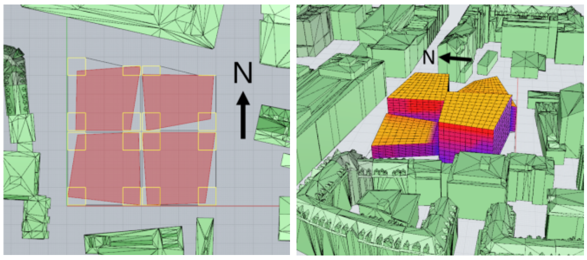

Fig. 2: Top (left) and perspective (right) views of the urban geometry model, with solar radiation calculation for summer solstice day. Left: yellow outlines indicate bounds for building footprint design variables.

Fig. 2 shows the 3D-model, with the urban context in green (taken from a 3D model of the city [6]) and the four office buildings with calculated solar radiation for a summer day. The model is set up using Rhino / Grasshopper native components. The decision variables are the building outlines defined by four corner points as x/y coordinates per building and the number of storeys (1 to 6, matching the adjacent buildings) with 4m height per storey. One corner point's y-value is fixed due to site constraints, therefore in total 35 decision variables are to be optimized by the SA. The total floor area of all four buildings can range from 1.600 m^2 up to 34.340 m^2, depending on the building footprints and number of storeys. Window to wall ratio is set fix to 50%.

P_{rent} was set to 70 CHF/m². In the idealized system costs to cover the heating demands are calculated assuming a reference gas boiler with η=0.94 and 0.09 CHF per kWh gas. Cooling is provided with an air conditioning system with a COP = 3. Electricity is purchased for 0.12 CHF during off-peak and 0.24 CHF during peak hours. A Zurich TRY weather file for the city centre was used. The heavyweight constructions for roof, floor, walls and windows match the SIA 380/1 [10] minimal requirements.

To increase the influence of building geometry on the energy demand, natural ventilation is allowed during occupied hours, and lighting is dimmed

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according to daylight availability. Night ventilation was not allowed due to security reasons. The control strategies are given in Table 1. Schedules for internal gains (occupancy, equipment and lighting) are according to SIA for office buildings [11]. Each building volume is divided into 4m high stories. Each storey is described by a single thermal zone. Schedules for all zones are identical.

Technologies include combined heat and power (CHP), heat pumps (HP), gas boiler, photovoltaic panels (PV), air conditioning (AC), batteries and thermal storages (TES). Fig. 3 describes the considered energy hub.

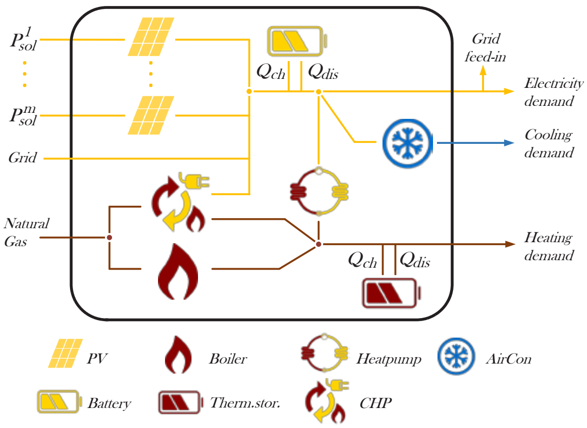

Fig. 3: Energy hub of the case study.

Model Parameters

Cost parameters are given in Table 2, carrier emission factors (EF) and prices in Table 3. Emission parameters of the reference building are 100 kWh/m^{2}a for heating and 120 kWh/m^{2}a for electricity [12] using a reference gas boiler with η = 0.94, resulting in 96.5 kgCO^2/m^2 total specific carbon emissions. Carbon targets are set to 80%, 90%, 100% and 110% reduction from the reference. The model is solved to a MILP optimality gap of 5%.

	Control mode (during occupation)
Cooling	Target 23 °C
Heating	Target 22 °C
Nat.vent.	Open at 21 °C
Dimming	Target 500 lx
Shading	Activate at 200 W/m^2

Table 1: Control set-points.

Equipment	Efficiency/COP	Unit Cost [CHF/kW]
AC	3	360
Boiler	0.94	200
Heat pump	3.2	1000
CHP	η_{el}=0.3 / η_{th}=0.519	1500
PV	0.18	300 CHF/m^2
Battery	0.92 charging/disch.	600
Thermal Storage	0.9 charging/disch.	100

Table 2: Parameters of devices.

Carrier	Carbon factor / price
Natural gas EF	0.237 kgCO^2/kWh
Natural gas price	0.09 CHF/kWh
UCTE-mix EF	0.594 kgCO^2/kWh
UCTE-mix price	0.12 off-peak / 0.24 peak CHF/kWh
Feed-in tariff	0.14 CHF/kWh

Table 3: Parameters of carriers.

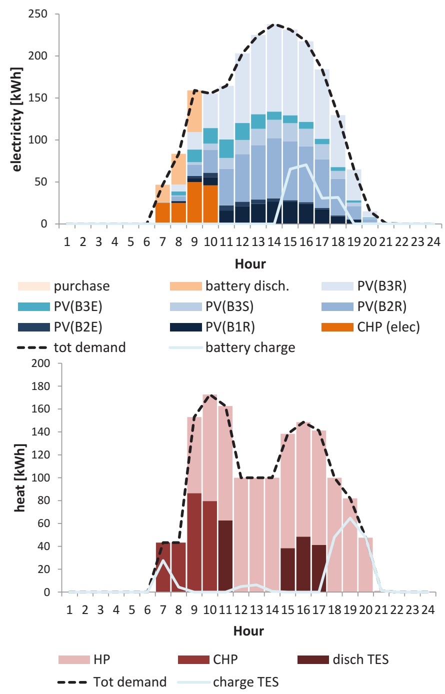

Fig. 4: Example energy balance for electricity (top) and heat (bottom), average March day.

Example Operation Schedule

The formulated MILP solves optimal hourly control schedules of the technologies, as well as technology choice and systems sizing. Example control schedules for heating and electricity for an average March day are shown in Fig. 4, including a technology breakdown on how the demand is supplied. The electricity demand includes charging of the battery (TES for heating demand respectively) and electricity sold to the grid.

4 RESULTS

To account for the stochasticity of the SA solver, multiple runs have been conducted. The consecutive algorithm was run 8 times and for each final solution the energy hub was solved for

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different carbon targets. The nested algorithm was run 3 to 5 times per carbon target. All optimization runs were terminated after 24 hours on a Win7 8-core Intel Xeon E5-2643 3.30 GHz with 128 GB RAM; four different runs were calculating at the same time per session. EnergyPlus accounted for most of the computing time, taking ~6 minutes for four buildings. The MILP solved within ~5 seconds.

Fig. 5 shows the final solutions of all runs for both methods plotted over the objective function value and the carbon reduction target. Red dots indicate solutions of the nested method. The black lines connect between different carbon targets, originating from individual solutions of the consecutive method. It can be seen that while for low carbon targets the optimal solutions of both the nested and the consecutive method are similar, for high carbon targets the nested method consistently finds better solutions. Especially with 110% carbon reduction, using the consecutive method results only in solutions which create losses, whereas the nested method finds solution with profits around 500.000 CHF.

While the found solutions for the 80% and 90% carbon targets are well distributed for both methods, the solutions for the 100% and 110% carbon targets found by the nested method are closely clustered at higher profits. This again indicates that the nested method can consistently find better solutions especially for high carbon targets.

Fig. 6 shows the amount of electricity purchased and sold from and to the grid, for both the nested and the consecutive method. For the consecutive method, the one best solution found without carbon target is used for calculating the final DES using the energy hub with different carbon targets. It can be seen that in order to meet the carbon targets, in the consecutive method more electricity generated by PV or CHP has to be fed into the grid than in the nested method. Also, the amount of electricity purchased from the grid is higher for the consecutive method.

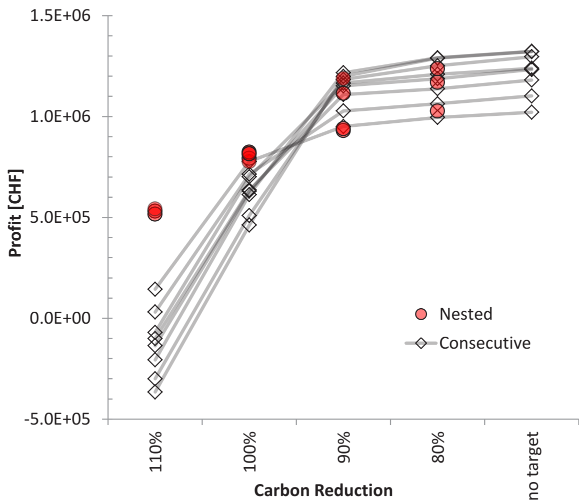

Fig. 5: Profit for final solutions of all runs.

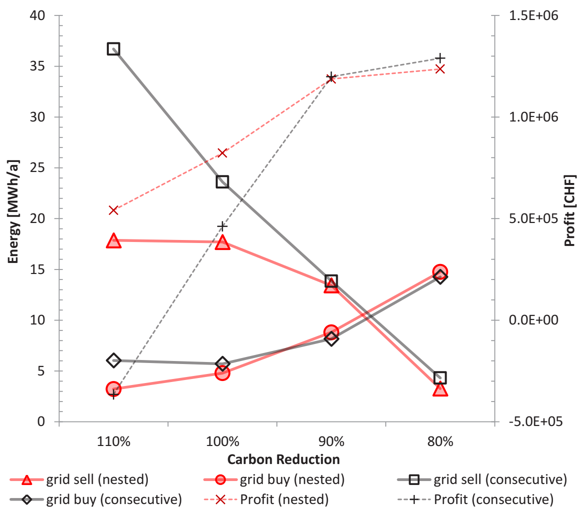

Fig. 6: Electricity purchased and sold to the grid.

Fig. 7 and 8 show the choice of energy technologies and their sizing for both the nested and consecutive method and for different carbon targets. For low carbon targets, both methods choose boilers, low capacities of PV, CHP and storages. While the capacity of the AC is constant in the consecutive method, in the nested method it is reducing, since the morphology can react to the energy system during the optimization. It is striking that in the consecutive method the capacity of the battery is drastically increasing with high carbon targets, while for the nested method it is not – for the same reason as for the AC: the carbon targets in the consecutive method have to be reached solely through the DES, whereas in the nested method the urban morphology (demands and potentials) can be optimized hand in hand with the DES.

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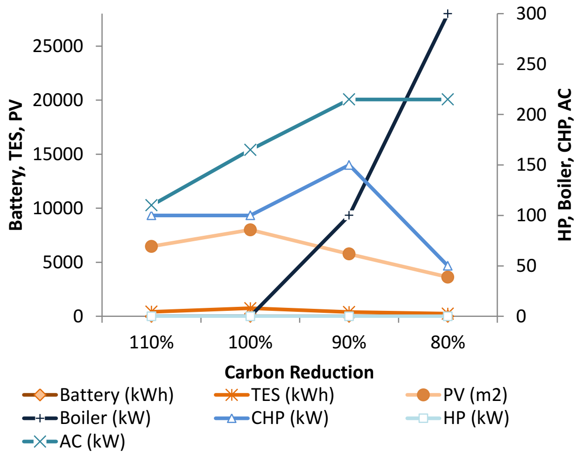

Fig. 7: Sizing and selection of technologies, nested optimization.

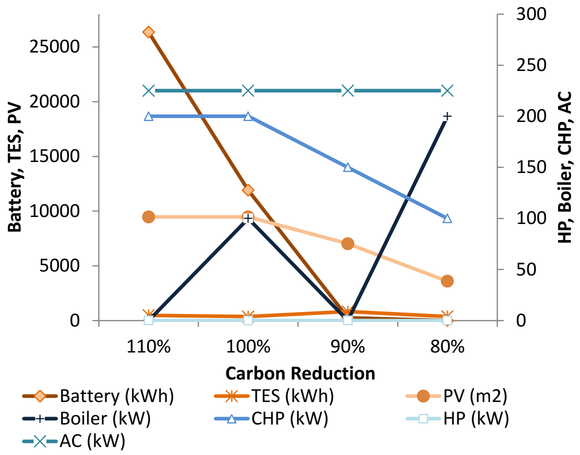

Fig. 8: Sizing and selection of technologies, consecutive optimization.

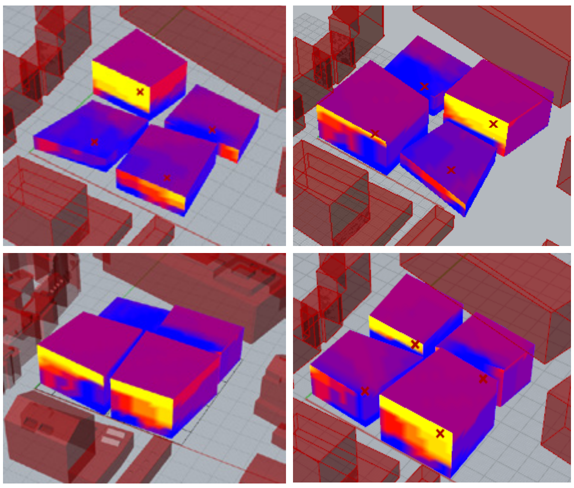

Fig. 9: Geometries of the best solutions found by the nested method for 110% (top left), 100% (top right) and 90% (bottom left) carbon reduction target, as well as the best solution found by the consecutive method (bottom right).

Fig. 9 shows the optimized building geometries for the best solution found by the nested method with 110%, 100% and 90% carbon reduction respectively, as well as the best solution found of the consecutive method before energy hub optimization. Solar radiation values for winter solstice are shown on the building surfaces. Different geometrical characteristics for each of the shown solutions can be identified, such as configurations where high buildings alternate with low buildings, or certain spacing between the volumes presumably to encourage daylight penetration. It is striking that the optimized geometries of the consecutive method are very similar to those of the nested method with 80% carbon reduction. However, the higher the carbon target gets with the nested method, the more geometric differences to the consecutive method are noticeable.

In general, increasing carbon targets lead to lower density. Characteristics of the optimized solutions of 80% carbon reduction target are narrow spacing between the buildings and large heights, whereas for higher carbon reduction target the spacings are increased and the heights reduced.

5 DISCUSSION AND FURTHER WORK

The results show that considering the design of the DES together with the optimization of urban morphology via a nested method leads to more profitable solutions for high carbon targets. This can be explained due to the fact that for low carbon targets the reference system calculation (assuming a gas boiler and electricity from the grid) is close to the optimal DES decided by the energy hub MILP, therefore little benefits can be expected from the energy hub MILP during the morphology optimization. However, for high carbon targets more sophisticated systems are necessary and the interplay between demands/ potentials and DES becomes relevant. This can be adhered by careful orientation and shaping of the buildings, which influence solar potentials, but also careful trade-off between total floor area (density) and related costs to reach the carbon targets.

It is expected that the sensitivity of urban morphology on the optimal solutions in reality is even higher, since many relevant factors have not been considered in this study. Especially accounting for micro-climatic effects in the urban context can have a significant impact on the building energy demands [13]. For example, the EnergyPlus simulations use the same wind pressures independent of how they are obstructed by their neighbouring buildings, which if considered would have an impact on the natural ventilation potentials.

Further work should address issues of micro-climate modelling in the urban context and allow more complex zoning of the building volumes. Also, losses and costs implied by the topology and typology of thermal networks [14], grid constraints [15] and a higher temporal resolution

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of at least 8760 hours instead of 12 average days to account for long term seasonal storages, will be included.

Allowing the acquisition of carbon credits and using land rent models or more precise data on rents should be considered to account for a more realistic trade-off between built density and the design of the DES for certain carbon targets. Hence, in areas of high rents, e.g. in central business districts (CBD) denser and still profitable morphologies would be possible while fulfilling the carbon targets by investing more in carbon credits instead of investing in more PV and CHP.

6 CONCLUSION

This study presents a novel framework for holistic urban morphology and district energy systems optimization, entirely within the 3D NURBS modelling software Rhino Grasshopper, a program widely used by architects and urban designers.

It has been shown that especially for high carbon reduction targets it is crucial to consider both urban morphology and DES hand in hand. In fact, only the holistic nested optimization method enabled designs, which generated profit instead of costs. Only in this way can knowledge of sophisticated multi-energy systems (energy hubs) necessary to facilitate the transformation towards carbon neutral cities be exploited in the design of sustainable buildings and neighbourhoods.

7 ACKNOWLEDGMENTS

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