GENERATION OF DYNAMIC ENERGETIC DISTRICT MODELS FROM STATISTICAL RELATIONSHIPS

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ABSTRACT

This contribution describes a new method for creating populations of generic geometric and energetic building models for energetic district simulation, based on very common information such as the population density, the mean building age, the mean energy efficiency of the buildings and the local climate conditions. These automatically generated district models allow to calculate typical heating and cooling demand cycles for simulation experiments including their spatial distribution.

The new approach is demonstrated by two different district types: a street village with a very low population density and four building blocks as a part of a high dense city centre in Berlin.

INTRODUCTION

During the last years new methods and models for the description of the energy demand of city districts and also the corresponding energy supply systems were developed (Robinson et al, 2009; Lauster et al., 2014; Huber et al., 2011; Inderfurth et al., 2014). This research is mainly focused on the modelling of the energy demand for a huge number of buildings, whereby each individual building inclusive its parameters and its location within the district is known.

The approach, which is described in this paper, aims by contrast on the dynamic energy demand modelling of "unknown districts" for cases, in which only a couple of general district parameters and boundary conditions - e.g. the total area of the district, the mean population density, the mean building age, the street layout and the local climate data - are available.

This approach might be of interest whenever there is a need for fast energy demand analysis of existent districts or during the early design process of new districts, where information about the individual buildings is not present.

The basic idea of the new approach consists in the usage of an universal dynamic and numerically fast low-order thermal building model, which is scaled in its quantity (overall number of buildings in the district model) and parameterized with the help of a set of statistical correlations. For this purpose selected statistical sources of the German building stock including data about construction and state as well as about demoscopic and economic aspects were carefully surveyed by the authors. This led to a whole range of more or less strict dependencies providing parameters and conditions for generic district modelling. For example the authors found a significant correlation between the population density of a district and the distribution between single-family houses, attached single-family houses and three different types of multi-family houses. This relationship - apart from some other influencing variables - enables the automatic generation of an appropriate settlement structure for a district model.

Simulating the so-created bunch of buildings by using the dynamic low-order thermal building model from the Modelica BuildingSystems library (Nytsch-Geusen et al., 2013) results in individual energetic building profiles and also in aggregated demand profiles of heating and cooling energy for the whole district.

Linked with urban maps and road layouts the generated district model can deliver reliable boundary conditions for system models of district heating or cooling grids as well.

LOW-ORDER THERMAL BUILDING MODEL FOR DISTRICT SIMULATION

The *BuildingSystems* library from UdK Berlin, implemented in the modelling language Modelica, includes thermal building models with different levels of detail, described in Nytsch-Geusen et. al 2014. For the generation of district simulation models a simplified low-order thermal building model was selected from the library and adapted for an efficient parameterization by a reduced number of essential parameters.

Physical model

Figure 1 shows the structure of the used low-order thermal building model in Modelica. This model includes eight thermal capacities, which represent groups of constructions with different boundary conditions of temperature and solar radiation:

- 1st thermal capacity: Opaque constructions, which outer surfaces face to the ambient (parts of the facades and the roof).

- 2nd to 5th thermal capacity: Four transparent constructions (considering the solar passive gains for the four main facade orientations), which outer surfaces are also face to the ambient.
- 6th thermal capacity: Opaque constructions, which outer surfaces are in contact with the ground (e.g. the building plate).
- 7th thermal capacity: Inner constructions, which are enclosed by the other constructions (e.g. inside located walls and ceilings).

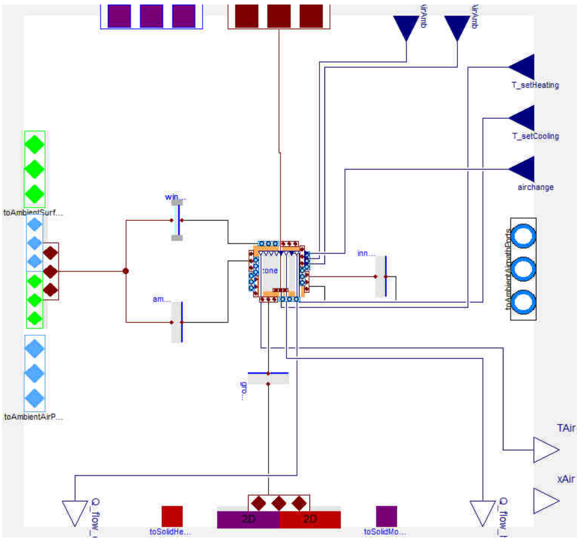

Figure 1 Used low-order thermal building model

An 8th thermal capacity describes the enclosed air mass within the building.

The capability of this low-order thermal building model to predict the heating demand in the context of district simulations is demonstrated by Inderfurth et al., 2015.

Parameterization

For large district models with potentially some hundred individual buildings the low-order thermal building model has to be parameterized with only few parameters. For this purpose a parametric geometry model for a box-shaped building was defined (compare with Figure 2), which calculates the surfaces and the volumes of the external and internal building constructions by following seven parameters

- width and length of the building,
- mean height of the storeys,
- number of storeys,
- mean length of the internal walls,
- mean window percentage of all facades and
- mean thickness of the constructions.

Further building construction parameters are the U-values of the external walls, the roof, the windows and the base plate, the mean volume specific thermal capacity of the construction as well as the transmittance of the opaque surfaces. The user behaviour is described by a set temperature for heating about 20 °C and a mean air exchange rate about 0.5 1/h.

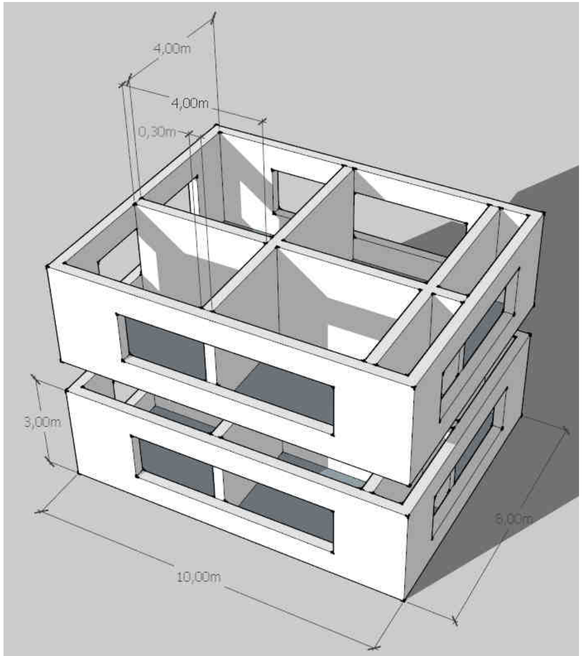

Figure 2 Geometry model for the parameterisation of the low-order building model in the case of the single family house

STATISTICAL CORRELATIONS FOR DISTRICT GENERATION

In the light of experience the calculation of the energetic behavior of existing buildings almost never meets the real situation. A reason can be found in the fact, that the level of detail in the energetic investigation of existing buildings is always limited by time and expense. Thus basic parameters such as construction dimensions and corresponding U-values are usually taken from rough estimates. As a consequence, the arising energetic calculations end up in results of considerable inaccuracy.

So when it comes to larger numbers of buildings investigating these one by one obviously seems to be a disproportionate effort for a more or less uncertain result. It is worth to have a look at less sophisticated - albeit less precise - methods of acquiring decent building parameters. The proposed practice is using correlation functions and lookup tables that are elaborated from statistical data reviews.

In 2011 an extensive survey called „Zensus 2011“ that was carried out by the German government. About 10 percent of the German inhabitants were interviewed about their living conditions (Destatis, 2011). Apart from the usual demographic and economical aspects this census introduced questions about buildings and flats, heating systems, energy consumption etc. for the first time. A number of obvious though not very strict correlations as well as some relevant benchmarks could be identified by reviewing these data.

Distribution of house types within districts

One of the relationships found by the authors in the context of the Open eQuarter project (Kaul et al., 2014) describes the distribution of house types within an area of given population density. The latter turned out to one of the most relevant benchmarks to parameterise the buildings of an unknown settlement structure in general:

Following correlations for portions of different house types (SFH: single family houses; SDH: semi-detached houses; SMFH: small multi-family houses; LMFH: large multi-family houses) were identified, dependent on the population density d_{pop}:

$$P_{Type\ i} = a + b \cdot ln(d_{pop}) + c \cdot ln^2(d_{pop}) + d \cdot ln^3(d_{pop}) \qquad (1)$$

The range of validity of these functions reaches from 150 to 15,000 residents per km^2.

Table 1

Coefficients for equation (1) of different house types

Type i	a	b	c	d
SFH	*1.07722*	*- 0.17400*	*0.03300*	*0.00254*
SDH	*- 0.05268*	*0.10300*	*- 0.01200*	*0.00018*
SMFH	*0.01146*	*0.02200*	*- 0.00500*	*0.00069*
MMFH	*- 0.02288*	*0.03300*	*- 0.01100*	*0.00115*
LMFH	*- 0.01312*	*0.01700*	*- 0.00500*	*0.00052*

Thermal quality of building constructions

The „Zensus 2011“ did not acquire any information about building features or construction details. But the gap could be filled by the „German Building Typology“, which provides valuable clues on how the thermal quality of different components changed in relationship to the house type and the building age in Germany.[1]

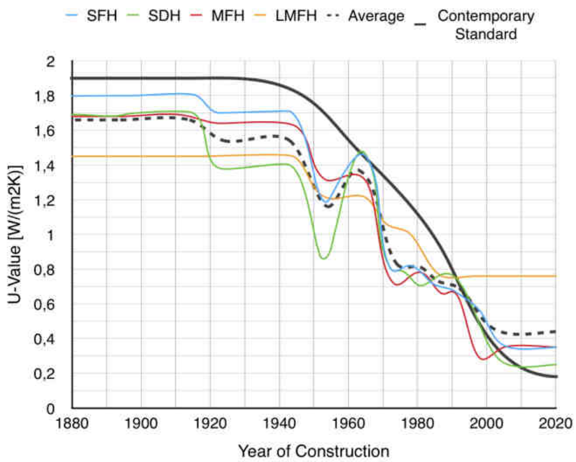

Figure 3 Typical U-values of walls as they are found today categorized by house type compared to the contemporary building standard at the year of construction.

As building quality vitally depends on the political and economical circumstances at the time of construction it was clear from the outset, that the data review in this case would not end up in a correlation of any kind. Nevertheless typical thermal component qualities could be recognized for different construction time ranges. Those were summarized in a bunch of categorized lookup tables delivering typical U-values for a specified component of a given house type in relationship to the year of construction. Figure 3 exemplary illustrates the U-values of the opaque parts of a building's facade for the different house types dependent on the year of construction. Further U-value functions were formulated for the roof constructions, the building plate and the transparent surfaces (windows).

GENERIC DISTRICT MODEL

The most important parameter for the generic district model is the mean population density d_{pop}. Together with the overall district area A_D the total population within the district *pop* is defined:

$$pop = A_D \cdot d_{pop} \qquad (2)$$

Number of buildings

The number of buildings of each house type (SFH, SDH, SMFH, MMFH, LMFH) can be calculated based on the statistical house type distribution of equation (1), e.g. for the single family houses:

$$n_{SFH} = \text{int}\left(\frac{pop \cdot p_{SFH}}{\sum_i p_{Type\,i} \cdot n_{Res,Type\,i}} \right) \qquad (3)$$

Assumptions for the house types

The number of residents per house type $n_{Res,Type\ i}$ depends on the number of flats per house type $n_{Flats,Type\ i}$ and the number of residents per flat $n_{Res,Flat}$:

$$n_{Res,Type\ i} = n_{Res,Flat} \cdot n_{Flats,Type\ i} \qquad (4)$$

In Table 2 the individual assumptions for each building type are listed.

Table 2

Assumptions for the building types

Type i	n_{Flats}	$n_{Storeys}$	width in m	length in m
SFH	*1*	*2*	*10*	*8*
SDH	*2*	*2*	*20*	*8*
SMFH	*3*	*3*	*15*	*12*
MMFH	*10*	*5*	*24*	*12*
LMFH	*30*	*10*	*20*	*20*

For all building types an unique storey height of 3 m and a mean window percentage the facades f_{Win} = 0.25 were assumed. The number of residents per flat was set to a default value of 3.5 and can be adapted to the individual situation of the district, if this information is present.

[1] As the IWU-survey was some kind of a snapshot in time. Due to intermediate refurbishment activities the found energetic qualities are in many cases better than the contemporary standard at the time of construction.

Building age distribution

The building age of each individual building within the district age_B is calculated based on a set of normal distributions for the given mean values of the building age of one or more building construction time periods $age_{P,i}$ and the belonging standard deviations $\sigma_{P,i}$. The portion of the buildings for each construction time period $p_{P,i}$ divides the overall number of buildings into separated normal distributions. In a second step these distributions are superposed to an overall building age distribution. Figure 6 illustrated by the case study of the street village an age distribution of 40 buildings for three construction time periods. Based on these individual building ages, the U-values for the building constructions of each building model are automatically parameterized by an look up table.

Placement of the buildings

The placement of the single building models within the district area is realised by a street model (compare with Figure 3):

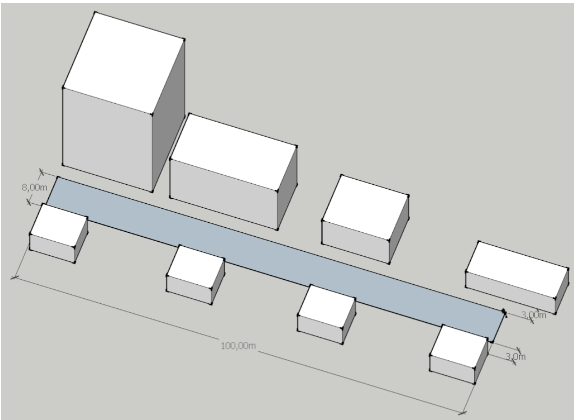

Figure 3 Street model (length = 100 m, width = 8 m, distance to buildings = 3 m) width 8 uniformly distributed building models: 4 SFH, 1 SDH, 1 SMFH, 1 MMFH, 1 LMFH

The generated building models are uniformly distributed on the right side or the left side or on both sides of the street model. In the process the placement algorithm takes the single buildings in the same order as they were generated before for the building model pool. The street model can be parameterized by its length, width and the distance to the buildings on both street sides. For a configuration of a district model, one or more of this street models have to be arranged to a wished street layout.

CASE STUDIES

As a first application of the generic district model two districts with an extreme different population density were modelled and analyzed regarding the their heating loads during three winter days:

1. A street village in the country side of Berlin with a extreme low population density of 400 inhabitants per m^2,
2. a part of an urban district in the centre of Berlin with a very high population density of 15,000 inhabitants per m^2.

In both cases weather data for Berlin, generated by Meteonorm were used as climate boundary condition.

Street village

The street village Klaushagen, 100 km North of Berlin, is considered. It is mainly structured by one street of 4,2 km length and 8 m width and an area of 0,63 km^2. The mean width of the village is assumed with 150 m (compare with Figure 4). The building stock of this village is described by 3 historical construction periods: first a long period from 1850 to 1940 ($age_{p,1}$=1900, $\sigma_{P,1}$=20 a, $p_{P,1}$=0.6), second a short period after the World War II from 1945 to 1955 ($age_{p,2}$=1950, $\sigma_{P,2}$=2 a, $p_{P,2}$=0.2) and third a period from 1995 to 2015 ($age_{p,3}$=1995, $\sigma_{P,3}$=5 a, $p_{P,3}$=0.2) after the German reunion in 1989. Figure 5 shows two typical houses of the street village, one of the second and one of the third construction period.

Figure 4 Aerial picture of Klaushagen, a street village 100 km North of Berlin, Germany (Source: Google Maps)

Figure 5 Typical buildings from two construction time periods of the street village

The given parameters for the size of the village, its population density and the three construction time periods lead after equation (2) and (3) to 40 building models with following age distribution (Figure 6):

Figure 6 Building age distribution for the street village based on three construction time periods

Figure 7 illustrates the generated street village with a 3D visualisation. Caused by the low population density the building population is dominated by stand-alone and attached single family houses and is completed by a few small and medium multi-family houses. The number of residents in the village is 252.

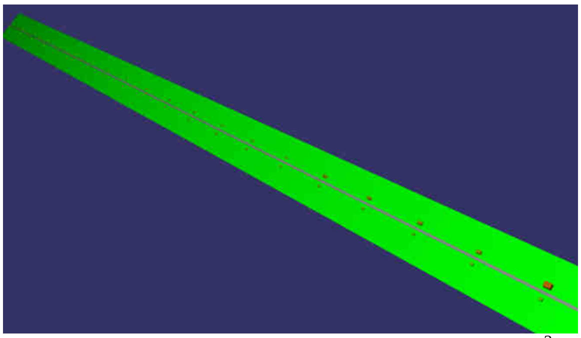

Figure 7 Generated village model (AD = 0,63 km²) with 27 SFH, 8 SDH, 4 SMFH and 1 MMFH

Figure 8 shows the overall heating load of the village (the sum of the individual heating loads of all 40 buildings) and the corresponding weather data for three winter days in the first week of January simulated with Dymola 2015 FD1. The heating rate for the village reaches a maximum about 0.4 MW during the third day when the outside temperature has its minimum of 3 °C.

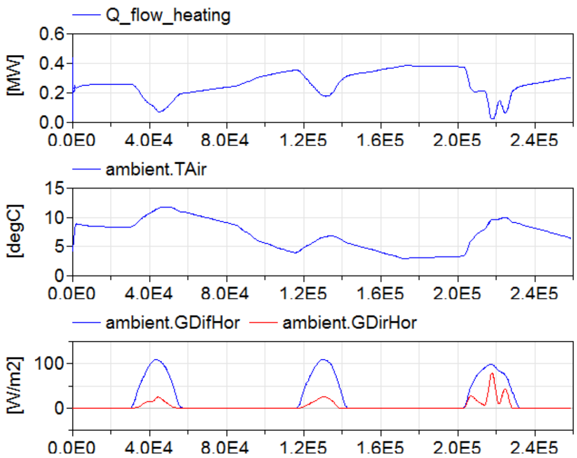

Figure 8 Overall heating load of all buildings of the street village and used climate data (outside temperature, horizontal irradiation)

Centre of a city

In the second case four blocks of the central located district Prenzlauer-Berg in the heart of a Berlin are considered. The district has a size of 440 m by 430 m width an district area about 0.19 km². and is structured by 15 streets with a length from 68 m to 220 m and a width between 14 m and 40 m (compare with Figure 9).

The building stock of this city district is divided in 2 construction time periods: first a period from 1880 to 1914 ($age_{p,1}$=1905, $\sigma_{P,1}$=10 a, $p_{P,1}$=0.95), in which the district was settled and a second period from 2000 to 2010 ($age_{p,2}$=2015, $\sigma_{P,2}$=5 a, $p_{P,2}$=0.05), in which gaps of the district were filled with newly constructed buildings. Figure 10 shows a typical row of five storey houses of the city district from the first construction period. The number of residents in the city district is 2,864.

Figure 9 Aerial picture for building blocks in Berlin Prenzlauer-Berg (Source: Google Maps)

Figure 10 Typical five storey city town houses from first construction period of the city district

In the first step the city district was generated based on the given street layout, the population density of 15,000 inhabitants per m² and the generated building age distribution.

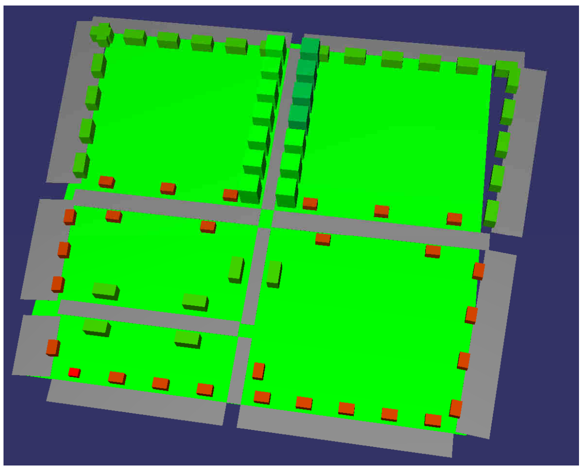

Figure 11 Generated city district model (AD = 0,19 km²) with 1 SFH, 27 SMFH, 28 MMFH, 14 LMFH

The 3D visualisation of Figure 11 shows the distribution of the generated house types within the district. Caused by the high population density the building population (70 buildings) is now dominated by small and medium multi-family houses and a few large multi-family houses.
Based on the additional information that large family houses are not present in the real district an alternative city district model was generated (see Figure 12). For this purpose the MMFH and LMFH were combined to one common building pool of LMFH. The spatial distribution of the buildings looks now much more close to the reality, the number of buildings increases from 70 to 105.

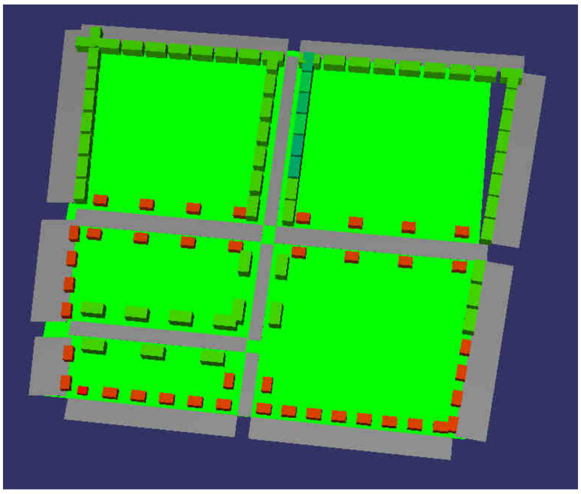

Figure 12 Generated city district model with suppressed LMFH models (AD = 0,19 km^2) with 1 SFH, 41 SMFH, 63 MMFH

Figure 13 shows the overall heating load of both models for the city district for the same three winter days in January and also mean area specific heating rate of all buildings:

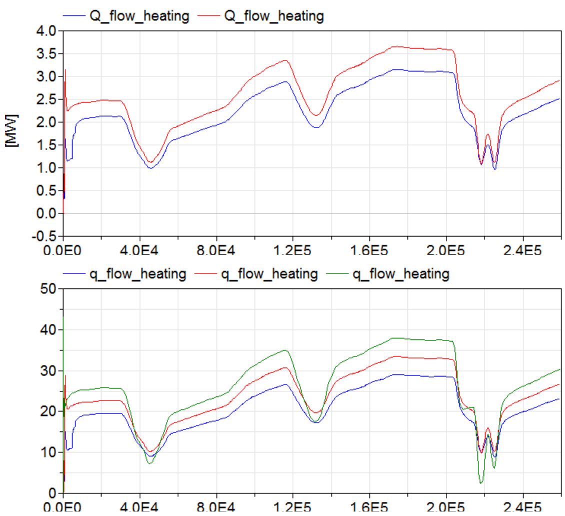

Figure 13 Above: Overall heating rate of all buildings of the city district. Below: Specific heating rate per m^2. Red: City district with LMFH, blue: City district without LMFH, green: Street village

The more realistic building type distribution with the suppressed LMFH reduces the level of the heat load timeline of the city district. Figure 13 shows in addition the specific heating rate of the street village (green curve). In general the specific heating rate level of the street village has higher values than the city district, because the reduced compactness of the smaller building types of the village leads to a higher demand level. But during increasing outside temperatures and solar radiation the smaller village houses with their reduced thermal masses indicates a lower specific heating rate than the city house population for a short time.

DISCUSSION

The results shall be discussed regarding the following subjects:

Use of statistical functions

The combined use of statistical functions like the distribution functions for different house types dependent on the population density, the U-value functions for different building constructions in combination with distribution functions about the building age and the dynamic low-order thermal building model enable in principal an automatic district generation. But there is still the weak point, that these functions at the moment are working independent from each other: it can happen, that a multi-family house with 10 storey's for a construction year of 1850 is generated.

Comparison with real districts

The comparison of generated district model in Figure 12 with the correspondent aerial picture in Figure 9 shows less buildings within the simulation model than real existent buildings. The reason is that up to now only residential buildings are considered in the district model approach. The analyzed city district in Berlin Prenzlauer-Berg also includes a large church, a supermarket, a primary school with open spaces and a lot of small shops, located in the ground level of the five storey town-houses.
Further the generated district model only knows solitary houses, the reality shows adjacent houses with common walls.
For this reasons, in a next step new house types (e.g. small, medium and large row houses and also public and commercial houses) shall be introduced, which can fill these gaps. When these extensions are realised, the base for real validations with measured energy demand values gained from existent districts will be present.

Numerical performance of the district model

The generation of districts models leads to a huge number of simultaneous simulated buildings models. Working with the 32 bit version of Dymola 2015 FD1 a district model with 200 building models seems to be a practical limit. Particularly the compilation time drastically increases for larger district models.

CONCLUSION AND OUTLOOK

A new method for a parametric generation of dynamic energetic district models driven by statistical relationships was developed and evaluated in two case studies. It can be stated, that the parametric approach is able to generate simulation models, which can calculate the overall heating and cooling load and its spatial distribution of residential buildings of a district, using only few parameters such as the population density, the mean building age and the street layout.

With the help of two case studies - a street village with a extreme low population density and a high dense city district - the flexibility of the generic approach was demonstrated. Additional general information (e.g. "all buildings of real district have 5 storey's or less" in the second case study) can improve the quality of the generated district models.

The next steps of the development will aim on the introduction of new building types, e.g. row houses for non detached district situations and the consideration of non-residential buildings. Also the simplified placement algorithm for an individual building within the given district area has to be extended with more smart approaches (e.g. either generation of "sorted building types" or "mixed building types" district models). Further new statistical functions will be added to the district model, which make the assumptions of the individual building models more precise (e.g. the size of the flats as a function of the population density) or the user behaviour of the residents more adapted to the present situation of the considered district (e.g. age distribution of the residents as a function of the population density → impact on the air change rate). After an acceptable number of model extensions, the first physical validations with measured energy demands of real districts can be started.

NOMENCLATURE

age_B = Building age of the individual building [a]
$age_{p,i}$ =Mean building age of a construction period [a]
A_D = Overall area of the district [km^2]
d_{pop} = Population density [Inhabitans/ km^2]
$n_{Flats,Type}$ = number of flats per house type [-]
$n_{Res,Type}$ = number of residents per house type [-]
n_{Type} = Number of buildings of a house type [-]
pop = Total population of the district [-]
$p_{P,i}$ = Portion of a construction time period [-]
p_{Type} = Portion of a house type [-]
f_{Win} = Window percentage of the facades [-]
$\sigma_{p,i}$ = Standard deviation of the building age of a construction period [a]

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