Computational methods for multi-criteria decision support in urban planning

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I think the most important thing technology can do in terms of the planning of cities is give people better information about the impact of decisions.

— Dan Doctoroff

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Abstract

Urbanization and climate change induce many challenges for today's cities. These challenges have to be faced by urban planners during complex planning processes that involve many stakeholders. Interactive computational approaches can provide assistance during these processes. The goal of this thesis is the development and demonstration of a computational framework that shows the impact of decisions taken during different phases and on different scales of an urban development project A key aspect of the proposed approach is its ability to quickly generate and efficiently handle a large number of alternatives.

Urban systems consist of many nested, partly autonomous elements. Moreover, they are embedded into larger systems and evolve constantly. The resulting unknowabilities comprise the uncertainty of current states and the unpredictability of future states of urban systems. The following computational methods are employed to address these aspects: (i) Multi-parametric programming allows to capture decision spaces of several actors with inherent trade-offs and tipping points. (ii) A corresponding model integrates five domains and four spatial scales. (iii) Multiple linear regression models serve to reduce uncertainty of input parameters. (iv) A data model allows to manage the large number of explored urban scenarios.

The developed system is demonstrated based on three case studies for which specific questions are stated. Starting with a greenfield development project in Europe, a first set of questions addresses the relations between the built density, the sustainability of the energy supply, the distribution of buildings, and the costs of different actors. A sensitivity analysis identifies the impact of changing energy prices on the preferred energy and urban systems. The results reveal tipping points regarding for example the preference for a decentralized or a centralized energy system. Changing from energy issues to livability aspects, relations between the built density, the share of parks, and the view on a landmark are quantified.
The other two case studies imply a move from Europe to Asia, and from new developments to existing neighborhoods, respectively. From this result different boundary conditions and questions concerning e.g. maximum achievable densities, energy autonomy, and cost-effective building refurbishments, accounting for heritage protection. A last set of questions addresses the influence of the considered spatial range on the outcomes:

increasing the range can reveal synergies leading to overall better solutions, such as the allocation of refurbishment subsidies to neighborhoods where more energy savings can be achieved for less investments. The addressed practical questions demonstrate the potential of the developed system to explore more thoroughly and quickly the decision space in urban planning.

Key words: urban planning, urban energy system, decision support, optimization, multi-parametric mixed integer linear programming, multiple linear regression, data model, Geneva, Singapore

Résumé

L'urbanisation et le changement climatique posent de nombreux défis aux villes d'aujourd'hui. Ces défis doivent être relevés par les urbanistes au cours de processus de planification complexes et qui impliquent de nombreuses parties prenantes. Les approches informatiques interactives peuvent fournir une assistance au cours de ces processus. Le but de cette thèse est le développement et la démonstration d'une approche computationnelle qui montre l'impact des décisions prises au cours des différentes phases et à différentes échelles d'un projet de développement urbain. Un aspect clé de l'approche proposée est sa capacité à générer rapidement et à traiter efficacement un grand nombre d'alternatives.

Les systèmes urbains sont composés de nombreux éléments imbriqués, en partie autonomes. De plus, ils font eux-mêmes partie de systèmes plus vastes, et évoluent constamment. Les inconnues qui en résultent impliquent l'incertitude des états actuels et l'imprévisibilité des états futurs des systèmes urbains. Les méthodes de calcul suivantes sont utilisées pour traiter ces aspects : (i) La programmation multi-paramétrique permet d'appréhender les espaces de décision de plusieurs acteurs, avec leurs compromis et points de bascule inhérents. (ii) Un modèle correspondant intègre cinq domaines et quatre échelles spatiales. (iii) Les modèles de régression linéaire multiple servent à réduire l'incertitude des paramètres d'entrée. (iv) Un modèle de données permet de gérer un grand nombre de scénarios urbains explorés.

Le système développé est démontré sur la base de trois études de cas pour lesquelles des questions spécifiques sont posées. Commençant par un nouveau projet de développement en Europe, une première série de questions porte sur les relations entre la densité bâtie et la durabilité de l'approvisionnement énergétique, sur la répartition spatiale des bâtiments ainsi que sur les coûts imputés aux différents acteurs. Une analyse de sensibilité identifie l'impact de l'évolution des prix de l'énergie sur les systèmes énergétiques et urbains privilégiés. Les résultats mettent en évidence des points de bascule concernant par exemple les conditions privilégiant des systèmes énergétiques soit centralisés, soit décentralisés. Au-delà des questions énergétiques pures, des aspects de qualité de vie sont quantifiés, tels que les relations entre la densité de construction, la part des parcs et la vue sur des objets urbains ou naturels emblématiques.
Les deux autres études de cas impliquent le passage d'un contexte européen à un contexte asiatique, et des nouveaux développements vers le redéveloppement de quartiers existants.

Il en résulte des contraintes différentes et questions nouvelles, concernant notamment les densités maximales réalisables, l'autonomie énergétique et la rénovation des bâtiments rentable et respectueuse du patrimoine. Une dernière série de questions traite de l'influence du périmètre considéré sur les résultats : l'élargissement du périmètre peut révéler des synergies conduisant à de meilleures solutions globales, comme l'allocation des subventions à la rénovation vers les quartiers où plus d'économies d'énergie peuvent être réalisées avec moins d'investissements. Les questions pratiques abordées démontrent le potentiel du système développé à explorer plus en profondeur et plus rapidement l'espace de décision en matière de planification urbaine.

Mots-clés : planification urbaine, système énergétique urbain, aide à la décision, optimisation, programmation linéaire multi-paramétrique en nombres entiers mixtes, régression linéaire multiple, modèle de données, Genève, Singapour

Zusammenfassung

Urbanisierung und Klimawandel bringen viele Herausforderungen für die Städte von heute mit sich. Diesen Herausforderungen müssen sich Stadtplaner im Rahmen von komplexen Planungsprozessen stellen, in die viele Akteure einbezogen sind. Interaktive Berechnungsansätze können diese Prozesse unterstützen. Das Ziel dieser Arbeit ist die Entwicklung und Demonstration eines Computersystems, das die Auswirkungen von Entscheidungen aufzeigt, die in verschiedenen Phasen und auf verschiedenen Ebenen einer Stadtentwicklung getroffen werden. Ein wesentlicher Aspekt des hier vorgeschlagenen Ansatzes ist die Möglichkeit eine große Anzahl an Szenarien schnell zu generieren und effizient zu verwalten.

Urbane Systeme bestehen aus vielen verschachtelten, teilweise autonomen Elementen. Außerdem sind sie sind in größere Systeme eingebettet und entwickeln sich ständig weiter. Die daraus resultierenden Unwägbarkeiten beinhalten die Unbestimmtheit aktueller Zustände und die Unvorhersehbarkeit zukünftiger Zustände. Die folgenden Computermethoden werden eingesetzt, um diese Aspekte zu integrieren: (i) Multiparametrische Programmierung ermöglicht die Erfassung von Entscheidungsräumen mehrerer Akteure mit den darin enthaltenen Kompromissen und Wendepunkten. (ii) Ein entsprechendes Modell integriert fünf Domänen und vier räumliche Skalen. (iii) Ein multiples lineares Regressionsmodell dient dazu, die Unsicherheit der Eingabeparameter zu reduzieren. (iv) Ein Datenmodell ermöglicht die Verwaltung der großen Anzahl an untersuchten Szenarien.

Das entwickelte System wird anhand von drei Fallstudien demonstriert, für die sich jeweils spezifische Fragen stellen. Ausgehend von einem Neubauprojekt in Europa, betrifft eine erste Reihe von Fragen die Zusammenhänge zwischen der städtebaulichen Dichte, der Nachhaltigkeit der Energieversorgung, der Verteilung von Gebäuden und den Kosten der verschiedenen Akteure. Eine Sensitivitätsanalyse identifiziert die Auswirkungen von sich ändernden Energiepreisen auf bevorzugte städtische Energiesysteme. Die Ergebnisse zeigen Wendepunkte unter anderem bezüglich der Bevorzugung eines dezentralen oder zentralen Energiesystems auf. Im Wechsel von Energiefragen hin zu Aspekten der Lebensqualität werden Beziehungen zwischen der Geschossflächenzahl, dem Anteil an Parks und dem Blick auf ein Wahrzeichen quantifiziert.

Die anderen beiden Fallstudien bedeuten einen Wechsel vom europäischen zum asiatischen Kontext sowie von Neubauprojekten hin zur Entwicklung bestehender Stadtviertel. Die resultierenden, unterschiedlichen Randbedingungen und Fragestellungen betreffen beispielsweise maximal erreichbare städtebauliche Dichten, die Energieautonomie oder kostengünstige Gebäudesanierungen unter Berücksichtigung des Denkmalschutzes. Eine letzte Reihe von Fragen befasst sich mit dem Einfluss des betrachteten räumlichen Bereichs auf die Ergebnisse: Eine Vergrößerung des Bereichs kann Synergien aufzeigen, die zu insgesamt besseren Lösungen führen, wie die Allokation von Sanierungszuschüssen auf Stadtviertel, in denen mit weniger Investitionen mehr Energieeinsparungen erzielt werden können. Die behandelten praktischen Fragen zeigen das Potenzial des entwickelten Systems auf, Entscheidungsräume in der Stadtplanung gründlicher und schneller zu erforschen.

Stichwörter: Stadtplanung, urbane Energiesysteme, Entscheidungsunterstützung, Optimierung, multiparametrische gemischte ganzzahlige lineare Programmierung, multiple lineare Regression, Datenmodell, Genf, Singapur

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Nomenclature

α	azimuth angle of sky patch
β	angle from north towards direction of building
δ	duration of time step
$\varDelta\psi$	view range around landmark
ϵ	elevation angle of sky patch
λ	binary variable for sky patch
ϕ	decision variables
$\varPi$	performance indicator
ψ	angle from north towards direction of landmark
ρ	continuous decision variables for computer/optimization
σ	reference size of technology
θ	decision variables for user, parameters for model
ξ	binary variable to indicte the existence or usage of an object
ζ	continuous decision variables for computer/optimization
A	area
af	annuity factor
C	cost
c	vector containing objective function coefficients
d	distance
dm	diameter
E	energy flow
e	specific energy flow (to area or length)
Em	emissions
em	energy-specific emission factor
f	rate-specific energy flow
gr	glazing ratio
h	height
hn	heating network
hts	heat transfer station

i	interest rate
ir	surface specific irradiation
l	length
lt	lifetime
n	quantity
o	operation rate of technology
pm	perimeter
pr	price
r	radius
rf	refurbishment factor for thermal energy demand
RR	rate of return
s	share
sr	surface ratio
V	matrix containing equality constraint coefficients
v	vector containing right-hand side parameters of equality constraints
W	matrix containing inequality constraint coefficients
w	vector containing right-hand side parameters of inequality constraints
w	width
x	x-coordinate
y	y-coordinate
z	elevation

Acronyms

ADE	application domain extension
ASHP	air source heat pump
BAR	building area ratio
CH	chiller
ERA	energetic reference area
FAR	floor area ratio
GFA	ground floor area
GHG	greenhouse gas
GML	geographic markup language
GSHP	ground source heat pump
HP	heat pump
HTS	heat transfer station
LHS	left-hand side
LUT	land-use transport models
LVF	landmark view factor

MAPE	mean average percentage error
MFH	multi family house
MILP	mixed integer linear programming
MOO	multi-objective optimization
MoPEC	modèle de prescriptions énergétiques des cantons
mpMILP	multi-parametric mixed integer linear programming
PSS	planning support system
PV	photovoltaic
RES	renewable energy sources
RHS	right-hand side
RMSE	root-mean-square error
SFH	single family house
VIF	variance inflation factor

Set members

com	commercial
dhw	domestic hot water
edu	educational
elec	electricity for lighting and electric appliances
heat	heat
les	local energy supplier
mix	mixed-used buildings
off	office
ow-oc	owner-occupants
pv	photovoltaic panel
rsd	residential
sc	space cooling
sfh	single family house
sh	space heating
unrfb	unrefurbished

Subscripts

ρ	continuous variables
ct	conversion technologies
sct	sector
xt	exchange technologies
ζ	discrete variables
air	air
aux	auxiliary

bl	block
blg	building
cst	constant part of equation
dir	direct
dm	diameter-specific
ecl	euclidean
en-loc	local electricity network
en-nat	national electricity network
era	energetic reference area
es	energy standard
exp	export
exst	existing
fcd	facade
fl	floors
fp	footprint
gfa	gross floor area
ghg	greenhouse gas
gr	gradient of piecewise linearized function segment
ic	intercept of piecewise linearized function segment
imp	import
inv	investment
l	length-specific
lin	linear part of equation
lm	landmarked
loss	network losses
max	maximum value
min	minimum value
mnh	Manhattan
net	net
ntw	network
obs	obstructed
op	operation
park	park
pc	parcel
pv	photovoltaic
rel	relative
res	renewable energy sources

rfb	refurbished
seg	segment
soil	ground
tot	total
unobs	unobstructed
view	view on landmark
wdw	window
wht	waste heat
wood	wood pellets
Sets	
Φ	all decision variables
Θ	decision variables for user, parameters for model
AZ	azimuth angles of sky patches
BL	blocks
BR	network branches
BT	building types
CB	cost balances
CT	conversion technologies
EF	energy form
EL	elevation angles of sky patches
ES	energy standard
ET	energy technologies
LC	locations of buildings or centralized technologies
OT	occupancy types
PC	parcels
S	segments of linearized function
T	times
UE	useful energy
XT	exchange technologies

Throughout this thesis the following notation is adopted:

Parameters Parameters of the optimization are denoted with italic letters.

Variables Decision variables including variables which are derived from decision variables are denoted with bold, italic letters.

Subscripts Subscripts are printed in roman font if the are used as labels and in italic if they are denoting variables (Mills, 2014).

Sets Sets are denoted with all capital letters (https://en.wikipedia.org/wiki/Set_(mathematics)#Definition).

Set indices Italic superscripts of parameters and variables are denoting set indices. They are written with the same letters as the according sets but are uncapitalized.

Set members Members of sets are also uncapitalized and further denoted by roman font.

Furthermore, following conventions are made:

Variables All decision variables denoted by ξ are element of $\{0, 1\}$. All other decision variables are element of $\mathbb{R}_{\geq 0}$, if not stated otherwise.

Sums Whenever a sum is drawn over a variable or parameter indexed over some set, the sum is drawn over the entire set of the given index, if not stated otherwise.

Introduction

Today more than half of the world population is living in cities (55 %). That share is constantly increasing: While 60 years ago urban population made up 33 %, it is expected to increase to 60 % in 2030. This progressive urbanization means that cities will grow by about 1 billion people within the next 12 years (United Nations, 2018). These cities account for about 50 % of today's global greenhouse gas (GHG) emissions[1]. The four largest sources of these emissions are the energy sector (65.3 %), the transportation sector (15.1 %), the residential sector (7.3 %), and the industrial sector (7.1 %) (Marcotullio et al., 2013). In order to mitigate global warming by reducing emissions, major energy savings and efficiency improvements are required.

These global trends induce many challenges for cities: urbanization leads to both dense cities and urban sprawl with spatially segregated land-uses (Brueckner, 2000; Brody, 2013). This again implies overcrowded or deserted parts of a city at certain times of the day or week and long ways to commute on a daily basis (Bhatta, 2010). A consequence of this are regular traffic congestions (Turcotte, 2011; Jansen, 1993) and the need for capacity expansions of public transport systems (Mani, 2013). The expectations of our working and living spaces also imply constant changes: the electricity demand for appliances in households and offices is increasing (de Almeida et al., 2011; Jones and Lomas, 2016); additionally, our needs for thermal comfort are causing shifts from heating to cooling demand (Aebischer et al., 2007; Synnefa et al., 2007). Furthermore, the demand for built area increases not only due to urbanization but also due to decreasing household sizes (Bradbury et al., 2014; Liu et al., 2003). At the same time real estate prices are increasing (Schneider, 2018), which makes living in cities less affordable to larger parts of society (McPherson, 2003).

In addition to these issues, the awareness of environmental implications of urbanized life increases: our cities are required to emit less GHG to mitigate global warming (C40 Cities, 2018), comprise cleaner air, water, and soil, (Shao et al., 2006; Chen, 2007) and become less noisy (Moudon, 2009). They should also contain more green, recreational

[1] if GHG emissions from thermal power plants that are located outside city borders but supply energy to cities, are assigned to cities

space, (Evans and Hartwich, 2006; Birch and Wachter, 2008) and counteract further losses in biodiversity (Seto et al., 2012).

Cities have to cope with all of above problems and trends simultaneously. But is that alltogether possible? And if so, how? While concerning all of us, these questions have to be faced in particular by urban planners.

Urban planning: a challenging task

Urban planning is understood today as a process which involves a continuous collaboration between many participants in order to agree on a solution for an urban development project (Batty and Marshall, 2012). One reason for urban planning having evolved into this process is that the entitlement to take decisions is distributed amongst the various urban actors. This induces that urban planners are primarily negotiators and mediators between the various interests. Reaching a consensus is achieved by three characteristic elements of a planning process: (i) *urban design* concerns the elaboration of concrete proposals, which respect (ii) specified rules, referred to as *codes*, and which (iii) by being approved or rejected, allow *development control* (Marshall, 2012). During this process a multitude of instruments is employed, referred to as plans, which differ in their overall and especially spatial detail and extent, and thus in the number of already taken decisions. Urban planning is notably different from urban design, as it is “more akin to the management of an ecosystem than the design of an individual artefact” (Marshall, 2012).

In conclusion, urban planners need to arbitrate interests of various urban actors and domains, take into account phenomena on large and small scales, and anticipate the often far-reaching implications of decisions. This planning process is often based on limited available information, and in the context of very diverse projects, whose extensions are not always easy to define. This implies that, in theory, many possible scenarios of the future city should be explored in order to take firm decisions (Allen, 2012, p. 82 f.). However, due to limited financial and temporal resources, often only a few of them are explored in current planning practice (Balling et al., 1999).

Interactive computational approaches bear the potential to improve on this practice (Salingaros, 2012; Bruno et al., 2011; Saleh and Al-Hagla, 2012). These approaches combine the intuitive, judgmental, and creative powers of humans with the capabilities of computers to quickly generate and handle a large number of alternative scenarios differing in many criteria. This work is about the computational aspects of such an approach by the identification, development, and demonstration of suited computational methods.

Review of computational approaches to urban and energy planning

In the following, literature dealing with the employment of computational methods for urban and energy planning is presented. Historically, energy planning in cities was rather a separated, often subsequent task to urban planning, which addressed itself more questions of land-use or urban form for example. Due to global warming and its implications for cities, energy needs to be considered earlier in the planning process (Cajot et al., 2015). Consequently, the literature is to some extent divided into the fields of urban planning and the planning of urban energy systems, which explains the structure of this section. Nevertheless, some authors address both fields together. These works are presented last.

Urban planning

Many computational approaches to urban planning rely on modeling. Model-based computational methods have been introduced in the urban field about 60 years ago. They can be sorted into three main classes: (i) Land-Use Transport (LUT) models, (ii) urban dynamics models, (iii) and models which represent individual agents as cellular automata, agent-based models, and microsimulation (Batty, 2009). Of these classes, this work is most in-line with LUT modeling. Hence relevant work belonging to this class and employing optimization is presented hereafter more in detail.

Land-use transport models typically focus on the relationship between urban form and function (Keirstead and Shah, 2013). Examples for such models are the ones of Ligmann-Zielinska et al., (2008) and of Kumar et al., (2016), who use Mixed Integer Linear Programming (MILP) to generate land-use plans on a city scale considering e.g. the compatibility of adjacent land-uses. Bruno et al., (2011) couple a parametric design software with a genetic algorithm to generate a multitude of urban plans and thus exploring the decision space of urban planners heuristically. Their model comprises five decision variables for location, urban function, density, proximity and mixed-use quality. Saleh and Al-Hagla, (2012) make use of parametric design without employing an optimization algorithm to explore the interactions between urban form and environmental aspects, namely the microclimate. Haque and Asami, (2014) take heuristic optimization for urban planning down to the floor scale by including building height and mixed-use via a continuous decision variable. Furthermore, they consider different actors in the form of governmental planners and land developers. The group “Kaisersrot” developed different computer tools for architectural or urban design from sub-floor to district scale employing statistical methods, concepts of self-organization, or optimization in form of genetic algorithms (Hovestadt, 2010). The examples they provide incorporate different combinations of urban form and function, livability aspects as densities, proximities and view, and economic aspects as construction costs.

The articles mentioned so far have in common that energy aspects of urban systems are only treated marginally, or are completely out of their scope. Some of the tools consider the city scale, others resolve phenomena on finer scales. Furthermore, these tools often treat only planning and design aspects of urban systems. The existence of several urban actors is only considered by Haque and Asami, (2014).

Planning of urban energy systems

Other computational tools focus on the planning, design and operation of the energy supply and distribution system of cities, without considering typical urban planning aspects like urban form and function or the livability of urban developments. Relevant reviews of those tools include the ones by Mirakyan and De Guio, (2013) and Huang et al., (2015), who compare tools that can be employed during different phases of the process of planning community or city-scale energy systems. Markovic et al., (2011) reviewed this kind of tools with an additional focus on the environmental impact of those energy systems. Allegrini et al., (2015) performed a review on computational methods that address the planning, design and operation of energy supply systems spanning from building to district scale. One of the conclusions drawn is that there were still no tools that can be used for parametric analysis on the urban scale and that conform to an optimization process. The review of Reinhart and Cerezo Davila, (2016) addresses so-called Urban Building Energy Models (UBEM) designed for operational energy demand estimation. The listed works have as common goal the application of physically detailed building models on a neighborhood or city-scale.

Tools for the planning of urban energy systems have mainly in common that they consider design and operation aspects. As for urban planning tools, the considered spatial scales are quite varying. However, due to the consideration of operational aspects, most tools consider finer temporal scales. The interests of different urban actors are generally not resolved.

Urban and energy planning

Tools that consider both energy and non-energy aspects for the planning of urban systems are presented in the following. Shi et al., (2017) have reviewed recently the efforts of coupling design generation software, with energy simulation and heuristic optimization algorithms to create and evaluate urban designs under energy aspects. Riera Pérez and Rey, (2013) use the decision support tool SméO to evaluate 3 urban renewal scenarios. Their work regards a large range of urban planning aspects and spans the building to neighborhood scale. Robinson et al., (2007) developed SUNtool for fast and physically rigorous analyses of interdependencies between urban form and building energy demand.

This is achieved by incorporating dynamic models, with a specific focus on shortwave irradiation exchange and user behaviour. The tool is demonstrated on a case study of 100 buildings with each two thermal zones, thus spanning floor to neighborhood scales. Optimization is achieved by parametric studies although a coupling with e.g. genetic algorithms was mentioned as a potential extension. Fonseca et al., (2017) use their tool CEA to examine the interactions between mixture of buildings' occupancy types, environmental performance in terms of emissions and noise pollution, and resilience of both energy and transport infrastructure. They cover sub-building scales with e.g. the calculation of user densities up to the scale of a new neighborhood of 25 ha. As for most previous tools the urban form and function are user inputs in form of different design scenarios.

The following tools additionally employ optimization methods: Keirstead et al., (2009) introduced SynCity, an integrated modeling framework for the design of minimum energy layouts in early-phase urban planning. This is achieved by introducing modeling of energy demand and supply into the field of optimization-based land-use models. In order to obtain a finer spatial resolution without significantly increasing computational costs MILP is used (Keirstead and Shah, 2011). The case studies presented by Keirstead and Shah, (2011) deal with the partly quantitative allocation of urban functions within a real district, which is separated into about 40 distinct sites, and a hypothetic, regular grid of 100 16-hectare cells. Since the decision variables are surfaces and densities, the scale range should be rather classified as block to neighborhood, thus neglecting phenomena on building or even floor scale. Both the sizing of energy utilities and networks and the consideration of costs and emissions were included in SynCity for hypothetic grids of 16 to 256 cells (Keirstead et al., 2012) and in the tool DESDOP of Weber et al., (2010). However, both works consider the design of the energy supply utilities as a sequential step after the allocation and sizing of urban functions.

The tool CitySim (Robinson et al., 2009; Kämpf, 2009) can be seen as a further development from the above presented SUNtool. Kämpf et al., (2010) couple CitySim with an evolutionary algorithm to optimize the design of a set of about 32 buildings with different, pre-defined block layouts in terms of their volume for their received annual irradiation offset by their thermal losses. Taking into account the surroundings of the buildings, the considered spatial scales span the buildings up to the district. The study focuses on the trade-off between urban form and solar potential. UMI is a Rhinoceros plugin for the design of new neighborhoods (Reinhart et al., 2013). It incorporates livability, energy and environmental aspects. The urban form for each scenario has to be specified by the user and is thus extrinsic to the model. Presented case studies range from floor to neighborhood scale. Parametric modeling and optimization can be achieved using Grasshopper (Rakha and Reinhart, 2011). Best et al., (2015) developed a model for early-stage urban planning considering densities and building functions, which allows to simultaneously optimize energy supply and demand on an hourly time scale using a genetic algorithm. The smallest covered scale comprises floors. A larger scale is represented via an aggregation of individually simulated buildings.

Summary

The last presented works demonstrate that some progress towards an integration of several domains within single tools was made during recent years. This concerns notably the traditional urban planning domains concerning livability aspects and urban form and function, and the energy planning domains concerning supply, transport, and demand of energy as well as their environmental and economic implications. However, criteria of the respectively other domains often have to be provided as inputs to the models. Furthermore, tools that come from the field of building simulation often aim to take detailed modeling to larger scales. As these tools need relatively precise information regarding urban form, they tend to focus rather on urban design than on urban planning aspects (Reinhart et al., 2013).

This leads to the second observation that tools consider different spatial resolutions, varying from the neighborhood scale down to the wall scale in case of some energy-focused tools. Some of the latter comprise also a finer temporal resolution. Related to the considered temporal scales is the consideration of different phases: again, it is mainly tools for the planning of urban energy systems that consider both the design and operation phase of systems. Lastly, it is notable that only the work of Haque and Asami, (2014) distinguishes between the interests of different urban actors.

Many of the reviewed tools have in common that they are designed to evaluate alternative scenarios and not to generate them. However, the generative aspect is very important as it allows to considerably increase the number of explored alternatives and to thus improve on common practice. Those tools that foresee a generation of alternatives by means of optimization, often rely on heuristic optimization methods. These methods are easier to couple to simulation models but also lack a measure of how close to optimality solutions are, and, although depending on the problem at hand (Branke, 2008, p. 61), are often slower in exploring the solution space.

In summary, integrated computational frameworks for urban planning are still missing that consider many domains, scales, actors, and phases and that are able to quickly generate and handle a large number of alternatives.

Topics of this thesis

Research goal and outline

Based on the gaps identified in the literature, the goal for this thesis is to develop a computational framework that allows to quickly generate a large number of alternatives in urban planning processes considering that these processes concern many domains, span many scales, go through several phases, and involve many actors. In order to assess which aspects of cities and urban planning should be considered, chapter 1 provides a systematic analysis of those systems. For this purpose, some insights provided by the complexity theory of cities are summarized and requirements for suited computational methods are deduced. The different parts of the computational framework that address those requirements are presented in the following four chapters. Chapter 2 presents the chosen methodology to generate many alternatives. This alternative generation incorporates (i) the existence of various actors with different, partly conflicting interests and (ii) the great freedom early in a planning process, which implies to make and test many assumptions and update those in the course of the further process. The developed optimization model that finally allows to calculate each alternative and various related criteria, is the subject of chapter 3. The reliability of those criteria is an important aspect of computational tools. This depends also on the assumptions required as input to such tools. Chapter 4 presents one computational approach to obtain more reliable input by the use of submodels, which allow to get from more basic, but more available information, as here the building geometry, to more detailed but more scarce information, as here the heating demand of buildings. The generation of many alternatives during urban planning processes implies that both many potential alternatives and much meaningful detail for those alternatives need to be managed, stored, and processed in computationally efficient ways. Those topics are treated in chapter 5. In order to respect the individuality of each planning project, it is required to develop versatile and widely applicable computational methods. Consequently, the framework is developed based on three case studies, presented in chapter 6. Chapter 7 finally demonstrates the capabilities of the developed computational framework to address the requirements identified in chapter 1.

Core contributions

In striving for the above stated goal, the core contributions of this thesis are:

1. the elaboration of computational methods to generate and handle a large number of alternatives
2. the integration of many different aspects of cities and urban planning in one optimization model and
3. the demonstration of the capabilities of the developed planning support system to address identified aspects characterizing cities and urban planning.

Contributions to each of the fields are listed on page 133.

Context

This thesis documents one part of the joint development of URB^{io}, a new, web-based planning support system[2]. Employing interactive optimization, which is realized by a user interface based on parallel coordinates and maps, URB^{io} allows to quickly and thoroughly explore decision spaces in urban planning. The second, complementary part of that development is described in Cajot, (2018), and deals with the human-related components of the interactive optimization approach, namely the integration of the topic of energy into urban planning, the employment of interactive optimization for decision support, and the implied aspects of human-computer interaction. He also describes the joint work to align the development to the needs of practitioners and to validate the practical relevance of URB^{io} via workshops and surveys.

[2]www.urbio.ch

Chapter 1

Requirements for computational methods in urban planning

Highlights

- Approaches to complex systems
- Characteristics of cities and urban planning
- Requirements for computational methods in order to address the different aspects of urban complexity

This chapter provides a systematic assessment of the characteristics of cities and urban planning with the goal to identify, how those should be considered by a computational framework. Therefore different approaches to complex systems are presented in section 1.1. Based on this general analysis of the field, selected aspects of urban complexity are individually addressed in section 1.2. In doing so, a transition from aspects of complex systems to aspects of cities and urban planning is performed. The chapter is concluded by stating requirements, potentials, and limitations of computational methods for providing assistance in urban planning in section 1.3.

1.1 Approaching complex systems

Complexity can be approached from different perspectives, each concerning different questions. Asking what makes up complex systems should reveal reasons for complexity (section 1.1.1). If the question is about what makes one system more complex than another, it is drivers of complexity that can be identified (section 1.1.2). And when asking for the implications of complex system, the answers should concern consequences of recognizing systems as complex (section 1.1.3). Naturally, the different approaches offer different definitions of complexity.

1.1.1 Reasons

This section lists six reasons for systems being described as complex. The term “reason” is used, as it comprises both a causal connotation (like “generator”) and an explanatory connotation (like “feature”).

Interacting parts

Complex systems are comprised of many parts, which are separated by boundaries. These boundaries are not always clearly determinable, as often the case for social systems (Johnson, 2012). Over these boundaries, the parts exchange matter, energy, or information. Hence the parts may, at least partially, be interdependent (Gershenson, 2008). The interaction of parts can give rise to non-linear system dynamics, including transitions and tipping points at which a minor change of a system parameter induces a change of the state of many parts (Crawford, 2016). In addition to this, with complex systems there is “no certainty that we have identified all the key components that are necessary for an acceptable understanding” (Batty and Marshall, 2012, p. 43).

Autonomous subsystems

Not only are the parts of complex systems numerous, interacting, of different types, and not obvious to determine, but some of them might be also individual, autonomous subsystems. The autonomy of these subsystems implies that decisions are taken by these systems within their capabilities and freedom. As being also interacting parts, these decisions are influenced by other subsystems and encompassing systems. Consequently, subsystems are likely to adapt to an encompassing system but also to influence it in turn (Johnson, 2012). This again means that the state of such an encompassing, complex system is the product of the influences of many subsystems, aggravating the understanding of the encompassing system as there is not a single designer to ask (Marshall, 2012).

Nesting

The parts of complex systems can be nested, which means that they are ordered into several levels. The parts at different levels are usually different, but highly interdependent, up to the extent that parts at upper levels are just existing due to the existence of parts at lower levels. Interactions between different levels can lead to “butterfly effects”, where single events on lower levels have large effects on higher levels (Johnson, 2012; Crawford, 2016).

Emergence

The term emergence is denoting the recognition that a whole is something besides its parts (Lewes, 1875; Aristotle, 4th century BCE). Emergence suggests that solutions can not be obtained by addressing parts separately and sequentially, but only by addressing them all together i.e. the whole system (Koffka, 1935, p. 176).

Evolution

The interaction of system parts, including the exchange of mass, energy, and information, spawns the dynamic aspect of systems. While any dynamic system could change only temporarily in the case of, e.g., oscillating processes, complex systems are often subject to irreversible transformations. These transformations imply transitions from one more or less stable state to another. Transitions can have varying temporal extensions, which means they can be sudden or gradual. Sudden transitions are also known as “tipping points” (Gladwell, 2002). The intermediate state between transitions is referred to as “phase” (Rickles et al., 2007). In accumulating changes, the systems are evolving. At each transition there is often more than one state a system can transform to. This causes even systems of the same class to be on unique trajectories (Marshall, 2012, p. 200) and aggravates the transferability of insights gained by observing one of its class instances. The performed trajectory often has an impact on the possibilities for further evolution (Read, 2012, p. 127), (Crawford, 2016).

Openness

Complex systems can be open systems, which are characterized by exchanges across their boundaries. Hence a reasonable analysis of such a system often requires to take into account those exchanges. However, the implications can go beyond this: If those exchanges are manifold and depending on the system itself (as in the case of subsystems) it might be appropriate to extend the boundary of the analysis at the price of having to consider more system parts. Moreover, the question about the extent of the analysis of a system could concern several dimensions, as space and time. An implied question could be, if it is required to regard the system behavior during one minute, one day, or one year. The question for the drawing of those boundaries is often an important one, as it might substantially influence the outcomes of an analysis.

1.1.2 Drivers

Taking a different approach to complex systems, upcoming questions could be: what makes systems increasingly complex? Or, what makes one system more complex than another system of the same type? Answers to these questions lead to the identification of drivers. Consequently, drivers possess a functional relation with complexity and should be measurable (van Goor et al., 2013). Examples of drivers are (Crawford, 2016):

- Number of parts (Baccarini, 1996)
- Degree of diversity (Baccarini, 1996)
- Degree of connectivity (Baccarini, 1996)
- Number of nested levels (van Goor et al., 2013)
- Current state in evolution (Adami et al., 2000; Wolpert, 2013) (Lineweaver et al., 2013, p. 5)
- Degree of openness
  - Type (information, material, energy), number and quantity of exchanged flows (Baccarini, 1996)
  - Size of the encompassing systems that could or should be considered (Aelker et al., 2013)

1.1.3 Consequences

The last considered approach to complex systems is made by asking for the implications of complexity for an analysis of such systems. The first listed consequences – potentials and unknowabilities – can be perceived both positively and negatively as they might for example aggravate an analysis of a system, but increase design possibilities. Finally, three advantages of complex systems over simple systems will be listed.

Potentials

Both evolution and the composition from many parts imply that complex system have many potential states. A measure of the number of states is Shannonian information (Shannon and Weaver, 1949), also interpreted as freedom of choice, lack of knowledge, or information entropy (Haken and Portugali, 2015).

Unknowabilities

The fact that systems can have many potential states results in the unknowability of complex systems. Marshall, (2012, p. 198 ff.) lists three unknowabilities: (i) the “unknowability of the system as it is”, (ii) the “unknowability of effects of interventions”, and (iii) the “unknowability of the optimal future state”. These unknowabilities partly result from one or more reasons for complexity, and they are also cumulative in the listed order (Marshall, 2012, p. 201). It is proposed to split the first listed unknowability into two in order to consecutively draw individual conclusions for implications on potential computational methods.

Unknowability of the present state. The fundamental insight that leads to referring to the present state of a system as unknowable, is the recognition that knowing and understanding all parts and specifiying the complete, precise initial conditions of a system is at least difficult (Marshall, 2012, p. 199), (Batty and Marshall, 2012, p. 35). Such a knowledge would imply to know both the value of all system parameters, and all currently ongoing interactions, i.e. the functional relationships between the system parts. However, the term “difficult” does not imply an impossibility as the term “unknowable” suggests. Indeed, from a theoretical point of view and at least what concerns the system parameters, every information might be determinable up to a certain error by, for example, inquiries or measurements. This reminds of the concept of epistemic uncertainty: uncertainties that are arising from a lack of knowledge of the system, are characterized as epistemic. There is “a possibility to reduce them by gathering more data or by refining models”. If this is not the case, the uncertainties are characterized as aleatory, since they arise from the natural variability of a system (Kiureghian and Ditlevsen, 2009, p. 105) (Thunnissen, 2003, p. 6, 13). The possibility to reduce epistemic uncertainty is often limited not only by technical constraints, e.g. the highest obtainable precision of available measurement methods for a specific value, but also by practical constraints like the availability of resources to conduct inquiries or measurements.

The concept of reducible and irreducible uncertainty is useful to rise the awareness among stakeholders in decision problems that some “uncertainties can be further reduced, albeit at a cost that may not be justifiable” (Kiureghian and Ditlevsen, 2009, p. 109). The distinction between epistemic and aleatory uncertainty, moreover, induces thoughts about reducible and irreducible uncertainty, the possible and the clearly impossible, where in the realms of the latter lies “knowing the future”.

Unknowability of a future state. While it is possible to determine the present value of some parameters, like prices in economic systems, as there is de facto only one valid value per time instance, the aleatory part in their uncertainty increases when considering future system states, or the efforts to reduce the epistemic uncertainty rise into the immeasurable, respectively. Reasons for the unpredictability of complex systems are the unknowability of their initial state, their system dynamics including phase transitions and tipping points, and emergence (Batty and Marshall, 2012, p. 35). Thus, the unknowability of a future state is even increased compared to the unknowability of the present state.

Unknowability of effects of interventions. Although the exact future state of a system is not knowable, the effects of some interventions are predictable, albeit to a very small extent both in time and detail (Allen, 2012; Keynes, 1937; Batty and Marshall, 2012; Marshall, 2012). In fact admitting that predictions of the impact of decisions were impossible, would advocate to let a system organize itself (Allen, 2012, p. 83). What "detail" concretely means, e.g. quantitative over qualitative, or more over less numerical precision, depends both on the system under consideration and the respective intervention. Nevertheless, in terms of decision making, it is of importance to be aware of the very small predictability of the effect of interventions and hence the very large unknowability (Batty and Marshall, 2012).

Unknowability of the optimal future state. Even if the effects of interventions are known, it is not necessarily clear with which goal to intervene. Reasons for this unknowability are the uncertainty of having identified all relevant system parts (page 10), the existence of many autonomous subsystems with an interest in the encompassing system, and the individual, and quite distinct evolution of certain systems.

While the optimal future state is to some extent better definable for artefacts, where it would be the finished product, it is already not possible for ecosystems, which can obtain different balances of species (Marshall, 2012, p. 200). In complex artificial systems there are also subsystems with potentially conflicting interests but, moreover, these interests are not necessarily clearly defined, and/or are likely to change with time due to, for example, the obtainment of a new system state, which might reveal new possibilities or make different possibilities seem more attractive. This unknowability of the optimal future state is related to the concept of "requirement uncertainty" (Thunnissen, 2003, p. 13 f.).

Benefits

Marshall, (2012, p.193 ff.) identifies three benefits of urban complexity, which should hold for other complex systems as well:

Functional capacity. Complex systems offer functional capacity "through properties such as hierarchy, symmetry or asymmetry, flexibility, redundancy or specialisation of different parts" (Marshall, 2012, p.194). This allows systems to be e.g. more efficient or more adaptable to different requirements.

Synergy. Analogous to emergence, which is itself a reason for complexity, synergy is related to the possibility that a whole is greater than the sum of its parts. Synergy arises from the existence of heterogeneous, complementary system elements that can serve several functions. For example, a building can have the function to house people, while a park serves their recreation. But regarded together and in combination with the system part "sun", the building can provide shading to the park, a function which is not foreseeable when each part is considered individually, and which is thus different from functional capacity.

Perceptual richness. This benefit concerns the observation that complex environments seem to be more appreciated by humans, probably since they evolved in a relatively complex environment (Marshall, 2012, p. 193). Hence this is rather a benefit of urban complexity or at least of those complex systems, which humans are part of and in which aesthetic design plays a role.

1.2 Addressed aspects of urban complexity

In the previous section different approaches to complex systems in general were presented. These approaches resulted in the identification of reasons, drivers, and consequences of complexity. Of those, seven aspects are discussed more in detail in this section: five reasons and two consequences. Evolution as reason for complexity is analyzed from two perspectives: the irreversible progression through system states and the unique trajectories that systems perform during this progress. Each of the following eight subsections starts with an identification of the specific characteristics of urban systems, i.e. cities or their planning, that correspond to a certain aspect of complexity. Then, the definition of a term will be provided where deemed required, which conceptualizes the according aspect of urban complexity. Using this term, the subsection are concluded by stating what is considered by the computational methods presented in the next chapter.

1.2.1 Parts of systems: domains

Parts of urban systems

Urban systems consist of the following parts:
Artificial environment

- built environment
  - buildings
  - open spaces: e.g. places, parks
  - urban infrastructure for the supply, storage, and transportation of energy, information, material and people, i.e. networks and related devices (conversion systems, data centers, vehicles)
- other, usually smaller artefacts of various functions
  - furniture, both in and outside of buildings, like benches or flower buckets (Gröger et al., 2012, p. 137)
  - household or office items, industrial machines etc.

Natural environment

- animals
- plants
- air
- ground
- water

Humans and their ...

- perceptions, interests, ideas, ideals, fears
- organizations (families, communities, companies, institutions)

The majority of these parts is in continuous exchange via material, energy, and information flows (Robinson, 2011).

Definition of domains

In the above list, urban system parts are ordered according to an anthropocentric perspective. This classification could be diversified by regarding the same parts from different perspectives: The part “ground”, for example, has different meaning and value if regarded from e.g., a land-use, an energy, an environmental, an economic, or an aesthetic perspective. In this work the term “domain” is used to refer to system parts considered from a certain perspective. This notion of domains emerges from system parts being perceived differently by humans. These differing perceptions can be non-exclusive, meaning that they are not necessarily conflicting: architects might see a building as a means to express their ideas of built form, while the employees of the local energy provider regard the building as a sink (and potentially also source) of energy, and the occupants perceive it firstly as their home. But the perceptions can be also exclusive and are thus, at least all besides of one, necessarily imaginative: Kwartler, (1998) provides the example of how artists in the 1960s in New York started to perceive warehouses as space for living, working, and shopping, while the owners still regarded them as warehouses. This results in a clash of urban functions, where the simultaneous realization of both is not possible.

Considered domains

Five domains of urban systems are considered in this work (figure 1.1):

1. **urban form and function** as the layout of cities and the distribution of services,
2. **society** such as density, distances, or the availability and quality of open spaces,
3. demand, supply, and distribution of **energy**,
4. its implications for the **environment**, and the
5. **economy** in form of costs and profits.

1.2.2 System of systems: actors

Autonomous subsystems of cities

Autonomous subsystems are special parts which differ from other parts in their ability to take own decisions (section 1.1.1). Although at the edge of the arrival of autonomous technical systems like vehicles, it is currently still only humans taking decisions in most of the cities worldwide. Furthermore, even in the close future, the autonomy of those systems is still going to be much smaller than that of humans.

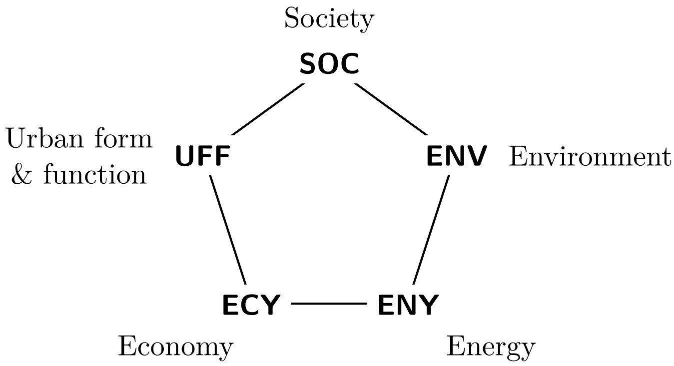


Figure 1.1 – Domains of urban systems addressed in this work

The existence of autonomously acting subsystems is the core reason for urban complexity (Portugali, 2016). The built environment alone is a simple system, as these parts do not interact by themselves, while the natural environment alone does not make them cities. Nevertheless, only addressing the existence of humans to capture the complexity of cities is falling too short. Portugali, (2016, p. 5) names a city a "dual complex system" and details the relation between the agent and the artefact: cities emerge from human interaction but are also framing it, which is referred to as "socio-spatial reproduction" in the field of social theory.

Autonomous subsystems of urban planning

The complexity is not only arising from the existence of and increasing with the number of autonomous subsystems, it is also increasing with their autonomy. One realization of this autonomy is that urban agents are, to a varying degree, willing and entitled to influence not only one domain of the urban planning system, but many (Batty, 2016; Crawford, 2016). They are thus playing several roles: The same human agent is, often simultaneously, for example a citizen, a pedestrian, a property owner, or an employee and thus has several, even conflicting interests. In pursuing their interests, human agents are forming groups, which on the one hand give more weight to their interests, and on the other facilitate the mediation in urban planning, as this formation delimits the interests to consider.

Definition of actors

The term "actor" is used to refer to a human or a group of humans with a specific, articulated, and common interest in a given planning project. The term is chosen for its prevalence in the field of the employed computational method (chapter 2).

Considered actors

Figure 1.2 shows the actors considered in this thesis. They are arranged loosely according to the domains in which they are interested. Those interests are described in section 7.4, when demonstrating how different actors are considered by the developed computational framework.

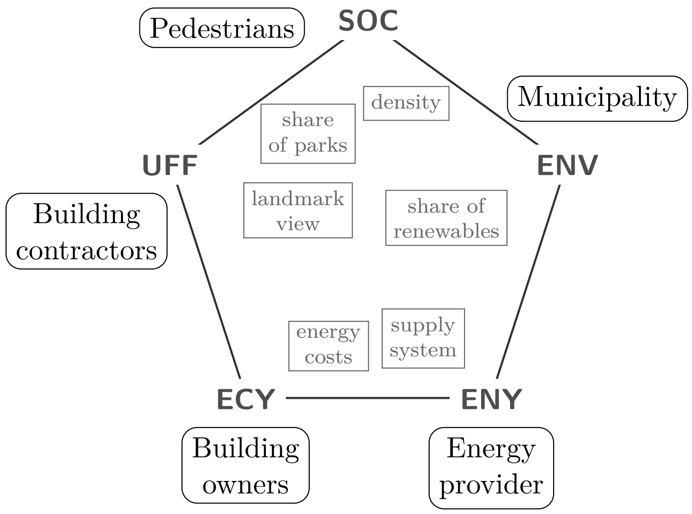


Figure 1.2 – Urban actors considered in this work (rounded rectangles), ordered by respective domains, and examples for criteria of their interest (rectangles)

1.2.3 Nesting of systems: scales

Nesting of cities

Cities are highly nested systems, partly physical, partly organizational. They can be perceived as consisting of districts made up of neighborhoods, blocks, buildings, floors, apartments, rooms, walls, etc. Which of these structures are visible, depends on the considered scale: while from far above only building blocks might be distinguishable, the observer needs to be relatively close to recognize windows within a wall. Additionally there are system parts that link the large with the small with subparts of varying sizes, like the electricity network of distinct voltages.

Nesting of urban planning

Also urban planning processes are nested. On the one hand this nesting reflects the spatial nesting of cities. For example, instruments like master plans exist on the city, district, or neighborhood level. On the other hand it reflects a temporal evolution of the planning process (Cajot, 2018). The according decisions are taken on different scales, both spatial and temporal, but influence each other: the decision about the density that a new neighborhood shall achieve, has ultimately an impact on the number of floors of each building.

Definition of scales

The term “scale” is used here to assess the fact that urban systems are nested. It is understood as order of magnitude (figure **??**) and each scale has an according typical unit. For example, the unit of the building scale is meters and the unit of the wall scale is centimeters.

Considered scales

Spatial scales. The considered spatial scales reach from the floor scale up to the neighborhood scale. The choice for the smallest scale is mainly due to the planning task of designing both horizontally and vertically mixed-use developments that foster social equality (Ligmann-Zielinska et al., 2005). The largest scale is selected in order to cover most of the phenomena that only arise when looking beyond the building scale, while remaining small enough that actual outcomes produced with the computational method can have a practical meaning (Riera Pérez and Rey, 2013).

Temporal scales. Depending on the case study either an hourly or a yearly scale is considered (chapter 6).

1.2.4 Evolution of systems: phases

Evolution of cities

Cities are constantly evolving: they grow or shrink in terms of area or population, whose composition (like age or social status) is also changing. These macro-scale changes are often perceptions of micro-scale changes: a population growth implies the transformation of green fields into urbanized land, or the densification of existing urbanized land, respectively. A change in the composition of a population due to, for example, gentrification, implies the transformation of the use of urbanized land in form of, for example, different kind of shops (Zukin et al., 2009). During these transformations a site evolves from e.g. a green field to a construction site, and from there to an “operated” set of buildings. The transitions between these phases are temporally more or less clearly delimited: at some point construction works on a new neighborhood start, at a later point occupants move in, and, much later, buildings might be demolished.

Evolution within urban planning projects

The idea behind urban planning is to intervene in this evolution of cities with the intention of improving them (Batty and Marshall, 2012, p. 44)[1]. Thus, in addition to the already indicated physical phases of urban systems – construction, operation, and demolition – one can state two virtual phases, namely planning and design, during which changes are not yet perceptible in the real city.

One factor making planning and design difficult, is that decisions are taken not only during both of these phases, but during all of the above stated phases. The reason therefore is the existence of many urban actors as addressed in section 1.2.2. Consequently, although the decisions of planners have a considerably high impact on the ultimately built neighborhood, their decisions are not the only ones affecting the final outcome. Some of their decisions that are made during early phases of the planning process, have ultimately to be realized by implementations during later phases of the process (Bruno et al., 2011). This holds especially if the decisions of planners take the form of postulated targets. An example therefore would be the target for a specific share of energy from renewable sources (RES), where the achievement of the target ultimately depends on the ensemble of decisions for energy supply technologies or the insulation of buildings.

The different urban actors decide partly based on knowledge that would be already available to the planners, but might be overlooked due to the sheer amount of it (e.g. spatially highly resolved information), partly based on knowledge that is just created by the planners as being a result of their decision. The decisions of followers also create knowledge, that on the contrary was not available upstream in the planning process, but might have affected the initial decisions (deVries et al., 2005). This dilemma theoretically can be overcome only by a simultaneous making of all decisions (Bruno et al., 2011). Although being quite hypothetical, the obstacles to such simultaneous decision making in urban planning are hereafter considered.

Due to the multitude of domains and scales affected, the amount of all decisions to be taken during a planning process is very high, spanning a considerably large decision space. In fact it is so large that a single individual could not hope to capture all interdependencies within this decision space and all its boundaries. A group of individuals would already more likely be capable to do so, which led to the rise of collaborative planning (Godschalk and Mills, 1966). However, it brings along limitations of communication and thus mutual understanding. Whether a single person or a group, there remains the limitation that they are not entitled by law to take all decisions. Although the legal situation might partly result from the recognition of the mental and communication limitations, a part of the decisions is intentionally left to followers to respect their freedom. This holds especially for more subjective or context-specific decisions about e.g. architectural design which

[1] This section is not about the evolution of urban planning. An according description is provided by e.g. Hall, (2014).

can thus not be decided "at once" and are almost impossible to anticipate. However, other decisions by followers are more rationally driven and thus easier to anticipate, and it is this kind of decisions, that this work aims at incorporating in the planning process. This process could then profit from the insight into the effect of decisions of the planners on those of the followers, by adapting the upstream decisions accordingly.

Definition of phases

In this work the term "phase" is understood as a limited period of evolution of both a city and a planning process. It groups certain tasks and activities, which are often only performed during this phase. Transitions from one phase to another have varying temporal extents, which means that phases can overlap.

Following phases of urban systems can be distinguished:

Planning (virtual) This phase comprises the definition of development goals. Depending on the context and the planning instrument, it can already specify e.g. the allocation of buildings (land-use). Although many urban actors are involved during this phase, the principal decision makers are typically public departments.

Design (virtual) This phase corresponds to the concrete sizing of parts of the built environment. The decision makers are typically property owners, architects and engineers.

Construction (physical) During this phase physical parts are built. The prominent example for involved urban actors are building enterprises.

Operation (physical) During this phase the physical systems are used. The decision makers are in particular but not exclusively the owners of the physical systems, like building owners or service providers as power supply companies.

Demolition (physical) During this phase the physical parts are destroyed. The prominent example for involved urban actors are demolition companies.

The assignment of decision makers reflect typical entitlements. Some decision makers are indeed involved in several phases, as for example local energy providers. At one moment different parts of a city are in different phases, and can pass through these phases also iteratively.

Considered phases

Of the five phases mentioned above, this work will deal with the planning, design, and operation of urban systems (figure 1.3).

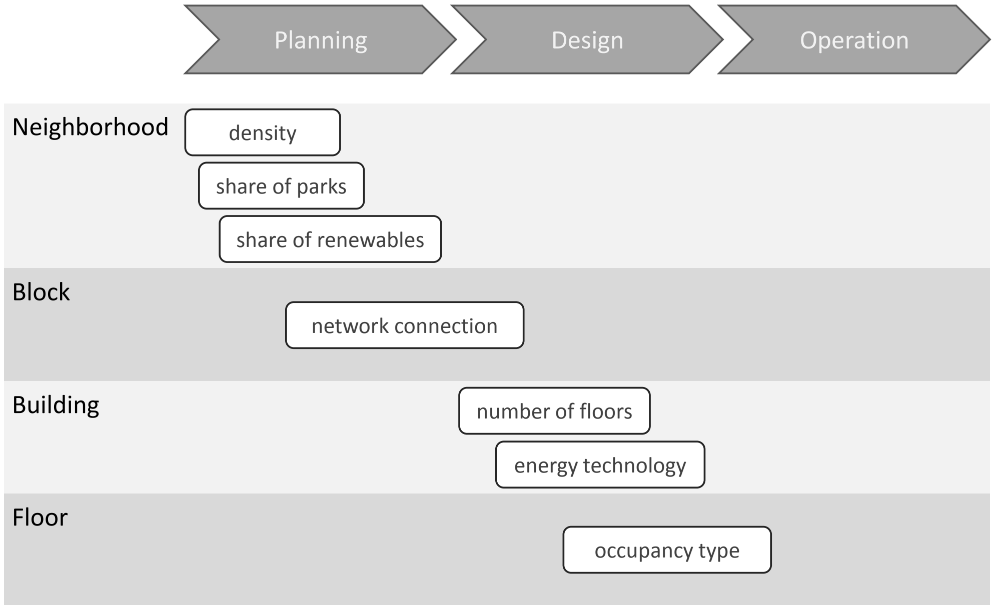


Figure 1.3 – Examples of decisions to be made by different actors during the here considered phases of urban systems and being implemented on different scales

1.2.5 Trajectories of systems: contexts

Trajectories of urban systems

Additionally to evolving with time, each city is evolving on an individual trajectory (Marshall, 2012, p. 200). Although, cities reveal self-similarity (Bettencourt et al., 2008) each city is different. Reasons for these differences lie in particular in:

Geographic location which determines:

- topography (shading, view, transport systems),
- weather, and
- culture (Hillier, 2012, p. 150).

Size in terms of e.g. population or area: shrinking cities face different, partly contrary, issues than metropolises (Hollander et al., 2009).

History as the past trajectory influences the future trajectory (Read, 2012, p. 127) (section 1.1.1): the presence of historic buildings in old cities implies both value and responsibility (Nasser, 2003).

Regional or national importance as e.g. political or economic centers.

Implications for urban planning

Due to these differences, solutions identified for a certain planning problem are context-specific (Crawford, 2016, p. 7f.) and thus not or not easily applicable to different planning problems.

Definition of context

With the term "context" it is referred to the individuality of each city and planning project, respectively.

Considered contexts

The three case studies considered in this work are lying in Europe and Asia, respectively. Thus their contexts due to their geographic location vary. This is taken into account by according meteorologic conditions and topography. Those are having an impact on energy demand and livability. Moreover, the case studies are located in two cities of different sizes. This will affect the considered target densities. The case studies are also differing in their historic context: one is about the construction of a new neighborhood on previously agricultural land (so-called greenfield development), another one is about the building of a new district on previously industrial land (redevelopment), and third one treats the further development of three existing neighborhoods (development). The latter implies for example that the protection of historical buildings has to be accounted for. The case studies are presented in chapter 6.

1.2.6 Open systems: ranges

Openness of urban systems

Cities are open systems since they are influenced by their "hinterland, competing cities and regions, the global society and economy, and ultimately the global ecosystem" (Marshall, 2012). Consequently, the system to consider is potentially very large.

Definition of ranges

The notion of ranges arises from the question about where the border for a system analysis is drawn and thus what shall be considered intrinsically and what is left extrinsic.

A “range” is different from a “scale”: while the scale defines the considered detail, the range defines how much of it is considered. For example for the temporal scale of seconds, the range can be 30 seconds or 3600 seconds and for the spatial scale of buildings, the range can be 10 or 150 buildings. Other authors refer to the temporal range as “horizon” (Sethi and Sorger, 1991), and the spatial range as “perimeter” (Alves et al., 2015). The distinction between “ranges” and “phases” is that phases have a contextual meaning, as defined on page 24. Moreover, phases cover more or less clearly defined ranges with start and end points and durations.

Considered ranges

Spatial ranges. Depending on the case study (chapter 6), between 49 and 265 buildings are taken into account. For one case study, the number of regarded buildings is varied in order to identify effects of the considered spatial range on the outcomes (section 7.7).

Temporal ranges. The temporal range for all case studies is one year.

1.2.7 Potentials of systems: information

So far the reasons of complexity listed in section 1.1.1 were found to hold for urban systems, especially cities themselves. The last two addressed aspects concern consequences of complexity and thus in particular the planning of cities.

Potentials of urban systems

Shannonian information and cities. As mentioned in section 1.2.2, urban actors turn the inherently simple system “city” into a dual complex system. The cognitive capabilities of urban actors comprise that they can remember the past and imagine the future. These capabilities make them not only natural planners and designers, but even make it hard for them to not plan and design (Portugali, 2016). All parts of their environment have more than one potential state, which means that they contain Shannonian information. Combining these potential states of the single parts implies that cities convey a very large amount of Shannonian information.

Semantic information and cities. Additionally, the urban parts have meanings to the different urban actors, which is referred to as semantic information (Portugali, 2016). This information is subjective, as seen in the example of warehouses in New York, on page 17. The transmittance of semantic information implies a common understanding, often in form of a common language. There is indeed a deeper relationship between semantic and Shannonian information but that is going beyond the scope of this thesis. Instead it is recommended to read Haken and Portugali, (2015) and Portugali, (2016) on this topic.

Considered information

Both Shannonian and semantic information are considered within this work.

1.2.8 Unknowability of systems: uncertainties

Unknowability of urban systems

Although some city parts are going to be equipped soon with a large number of sensors, capturing really every bit of information is behind the horizon, not at last due to privacy considerations (Woyke, 2018). According to project partners involved in this work, their current situation is indeed characterized by a lack of information and of temporal or financial means to acquire this information before taking decisions. The unknowability of the present state is especially an issue for the planning of the further development of existing city parts. For new developments, the existing mainly has implications on decisions when those developments are seen in their local context as there will be an interaction with existing surrounding areas. Regardless of this, urban planning is facing all three other unknowabilities as well: "one could say that unknowability is the enemy of planning. The challenge of planning becomes one of how to intervene in or attempt to organise a largely artificial open system where there is not full knowledge of the system; where even if the current state is known, the outcome of interventions is unforeseeable; and even if outcomes were reasonably foreseeable, the optimal outcome would not be specifiable in the first place." (Marshall, 2012, p. 201) Nonetheless, the dilemma arises from the fact that, due to their professional occupation, humans *have to* plan, due to their imaginative capabilities (section 1.2.7), *want* to plan, and, since simply hoping for the best is not better than striving for it (Allen, 2012, p. 83), *should* plan. In combination with unknowabilities, this leads to the necessity of making assumptions. Naturally, it is preferable to need to make less assumptions and, if they have to be made, the closer they are or will be to reality, the better. Making assumptions closer to reality implies the reduction of all kind of uncertainties.

Considered unknowabilities

The four unknowabilities of a current state, a future state, the effects of interventions, and the optimal future state are addressed in this work.

1.3 Implications for computational methods

Based on the analysis of aspects of urban complexity presented in the previous section, conclusions for the employment of computational methods to capture this complexity are drawn. This includes the definition of requirements, the outline of potential approaches, and the statement of limitations.

1.3.1 Domains

Addressing urban complexity with computational methods requires to consider not only many parts of the system but also many perspectives on those parts. The consideration of system parts and their relations implies usually the implementation and employment of some sort of models. The number of considered parts and perspectives is limited by the knowledge about the properties of objects and their functional relations and by computational power. The aspect of domains is addressed in chapter 3.

1.3.2 Actors

When dealing with complex systems, the autonomy of subsystems must be taken into account. The decision making of these subsystems can be considered intrinsically or extrinsically. For both approaches the various interests have to be explicitly stated and provided as input to the computer system. The difference is that these interests have to be stated (i) for intrinsic consideration in the form of predefined rules and (ii) for extrinsic consideration in the form of subjective preferences that consequently need to be updated more frequently. An example for an computational approach that considers the interest of autonomous subsystems intrinsically is agent-based modeling (ABM) (Gilbert, 2008).

The need for a frequent update of user preferences implied by an extrinsic approach, however, requires a methodology foreseeing interactivity and the identification of a suited human-computer interface. Two general directions are imaginable to let the computer know the interests of urban actors: on the one side a mediator knowing about the interests of the various actors takes the task of reflecting them when using the tool. In fact, planners are already today negotiators between various urban actors (Batty and Marshall, 2012, p. 37) and thus proficient in learning and incorporating their respective interests. The other direction is that many actors use such a tool collaboratively, and thus participate in the planning process. This approach also allows to account for the interest of many individual actors instead of grouping them.

While the requirements for a methodology suited for interactivity is addressed in chapter 2, further details concerning the human-computer interaction and decision making are presented in Cajot, (2018).

1.3.3 Scales

The computational method should allow to consider effects on different scales. However, for computational methods there exists generally a trade-off between considered scale and computation time: in general, the finer the scale, the longer the time. Scales are addressed in chapter 3.

1.3.4 Contexts

In order to account for varying contexts of urban planning projects it is required to develop a versatile and widely applicable computer tool. The aspect of contexts is addressed via the development and application of the computational system based on three different case studies, presented in chapter 6.

1.3.5 Ranges

From the aspect of cities being open system results that exchanges across boundaries have to be accounted for and that considered ranges should be flexibly definable according to the planning project at hand. As for scales, there is generally a trade-off for computational methods between considered range and computation time: in general, the larger the range, the longer the time. The effect of considering various ranges for an analysis is demonstrated in section 7.7.

1.3.6 Phases

A core requirement for a computational method that shall assist urban planning is to show how decisions would influence each other. In the course of this the method must account for the fact that many decisions are taken during different phases of an urban development. A further consequence of recognizing cities as systems subject to evolution is to also understand planning as an evolutionary process. From this results the importance of being able to update initial conditions and assumptions: the computational method has to allow to easily and quickly change almost every input parameter. Furthermore, the process requires to quickly discover the implications of updated conditions, which implies a demand for short computation times. Thirdly, since many actors are involved, the outputs of the computational system should be meaningful and easy to understand. And last, the program should also be easy to use and allow for collaborative usage (Mirakyan and De Guio, 2016; Russo et al., 2018). However, consequences of complexity confine the usage of such a computational system.

Unknowability of effects of interventions

The unknowabilities of complex systems induce that it is not possible to make detailed predictions for those systems (Batty, 1982). Thus computational methods dealing with complex systems allow to gain qualitative rather than quantitative outcomes. Consequently, they should be primarily used for the following purposes:

- to determine causal relations between conditions and expectable development patterns (Crawford, 2016),
- to get an idea of potential future states, where future states are not determined up to their last value or element, and are even not single states, but classes of similar states (Allen, 2012, p. 82 f.), and thus containing some Shannonian information,
- to establish reference cases for actual development (Allen, 2012, p. 84),
- to assess the robustness of planned interventions (Allen, 2012, p. 82 f.),
- to identify critical parts and processes (Batty, 1982, p. 19), and
- to sharpen the understanding and positions of decision makers (Kac, 1969, p. 699).

Unknowability of the optimal future state

The identification of potential future states in return allows to identify and agree on preferred future states and ultimately to undertake efforts to achieve them. Hence, computational approaches should enable to easily identify states that are better in respect to predefined targets. As there might be many targets, the method has to incorporate potentially conflicting goals and reveal trade-offs and synergies between them. The identification and proposition of many potential future cities could also assist undecided actors, or actors with less well defined goals, to articulate at least agreement or disagreement with aspects of certain solutions. Solutions could then emerge from the interaction of many users and the tool. The aspects of phases and the two last listed unknowabilities are addressed in chapter 2.

1.3.7 Uncertainties

In general, uncertainties should be reduced or quantified, wherever possible.

Epistemic uncertainty

Potential approaches to reduce certain aspects of epistemic uncertainty are the refinement of models or the use of additional models, and the acquisition of more data. These approaches are limited by technical and practical constraints. Chapter 4 describes the approach followed for this work.

Aleatory uncertainty

Aleatory uncertainty can be addressed for example by quantitative sensitivity analyses (Saltelli et al., 2008). The suitability of the developed computational system for sensitivity analyses is demonstrated in section 7.2.

1.3.8 Information

A computational method is required that allows to manage and store many potential states of a city (i.e. Shannonian information) and at the same time much, meaningful detail (i.e. semantic information) for those states. A physical implication of this are memory requirements.

This aspect is addressed via the adoption and further development of a data modeling standard, and the development of a data model suited to meet above stated requirement. Both are presented in chapter 5.

1.3.9 Benefits

Despite of the non-trivial limitations and the many requirements for a computational framework addressing complexity in urban planning, there are potential gains in implementing such a tool. These gains come along with the benefits listed on page 14.

Functional capacity

Functional capacity implies adaptable systems. A computational system truly able to capture the complexity of the subject is itself more adaptable to different requirements, e.g. in form of questions it shall address.

Synergy

The sketched computational system is likely to consists itself of several parts with distinct functionalities: for example, a model allows to instantiate problems, a solver identifies solutions, and a database stores information. However, it is only their combination into one system that allows to identify desirable future states of cities. Hence such a system can be said to exhibit synergies.

But it is not only the computational system itself that reveals synergies, it is also the process of modeling. Since models are representations of a complex reality, however simplified, they can become – to a lesser degree – also complex. A manifestation of this is that with the implementation of each additional system part or scale, an increasing number of relations with other already modeled aspects can be captured. To the suggestion of Marshall, (2012, p. 195) that "synergy is most directly of benefit to the designer" can be added that this should hold for both, real and virtual systems.

1

Chapter 2

Optimization method

Highlights

Presentation of an optimization method to ...

- capture trade-offs between conflicting interests
- generate alternatives
- allow to update any numeric assumption

The content of this chapter is building upon material published in (Schüler et al., 2018b).

The previous chapter has brought forth aspects of urban complexity that are further addressed in this work by computational methods. This and the following chapter will present those methods in detail.

Computational methods often imply modeling. There are various types of modeling, each of which developed and suited for different purposes. Examples are simulation and optimization models, which both capture functional relations between system components, but result in either determined or underdetermined, respectively, equation systems. Consequently, simulation models are especially suited to evaluate system states by calculating from the values of all input parameters the corresponding values of the output variables. Optimization models are designed to identify optimal system states by determining the values of variables that optimize an objective function for the given values of input parameters.

Another group of models is formed by statistical models that need to be trained on data sets. This training forms part of the model building phase. Once fitted, the models can be used to predict outputs from unseen data. They thus serve the same purpose as simulation models but do not require an understanding of the functional relationships of the system at the price of inherently containing prediction errors.

A fourth type of models treats the organization of parts of systems, called entities or features, their properties, referred to as attributes, and their relations, or associations. The result of this ordering are conceptual data models, which can then be translated via logical data models into a physical data model, which finally describes how data is physically stored in e.g. tables or files.

The specific mathematical formulation that a model obeys to, is referred to as method. Examples are the finite element method for simulation, or regression methods for statistical modeling.

The aspects of urban complexity that concern the existence of various actors and several planning phases are addressed in this chapter via the employement of multi-parametric mixed integer programming.

2.1 Generating alternatives: multi-objective optimization

The characteristic of urban systems of passing through several phases revealed a core requirement for a computational system, which is to show how decisions influence each other (see section 1.3.6).

In general, two approaches exist to support decision making (Hwang and Masud, 1979): multiattribute decision analysis (MADA) focuses on the evaluation and comparison of pre-defined alternatives based on a certain set of criteria that reflect the decision maker's interests. Methods following this approach are also noted as alternative-driven. In contrast, multi-objective decision analysis (MODA) focuses on the generation of alternatives according to predefined criteria, which thus become objectives, if they shall be optimized, or constraints if they shall be satisfied (Cajot et al., 2018).

While both decision support approaches have their strengths and justification, the alternative-driven approach (i.e. MADA) has the following drawbacks: the pre-definition of alternatives either by a human or by computational methods (e.g. Monte Carlo simulation) (i) requires additional human work or is computationally relatively ineffective and (ii) risks to miss optimal alternatives.

Value-driven approaches (i.e. MODA) employ for example computational optimization methods in order to overcome those drawbacks. These methods foresee that not all decisions are made by the human, but some of them – represented by so-called decision variables – are made by the computer. However, the computer decisions are not made randomly, but in such a way that the criteria defined by the human are optimized.

Despite of being an effective method for decision support, some restrictions need to be addressed when speaking about optimization in the urban context. First of all, there is no such thing as the "optimal city" and thus no single optimal outcome of a planning process (Marshall, 2012). One reason for this is the existence of several, potentially conflicting interests of different urban actors. If "optimization" is applicable, then it is meant as the identification of an optimal trade-off between these conflicting objectives (Batty and Marshall, 2012). Consequently, only optimization methods allowing the evaluation of trade-offs can be considered. This is satisfied by multi-objective optimization (MOO) methods, which offer Pareto-optimal solutions, where one objective can not be improved without worsening another.

2.2 Capturing decision spaces: multi-parametric programming

A further restriction of optimization in the urban context is that optimality lays not only in the eye of the beholder, but that this vision also changes with time. This makes it impossible to define and strive for an optimum future state (Crawford, 2016). Thus urban planning is not to be about obtaining and maintaining an optimum state, but about the continuous improvement towards what is currently regarded as better than the status quo.

Consequently, if optimization is to be seen as a useful method for urban planning (for the above stated insight of being helpful to generate alternatives), it should be employed not with the goal of defining an optimal state whose achievement urban planners should strive for, but to inform the continuous process of urban planning by identifying which decisions lead to improvements and which ones do not (Batty and Marshall, 2012, p.42), (Allen, 2012, p. 83). It is thus a shift from the object "city" to the process "planning" that reveals the benefits optimization can bring, namely by showing the impact of the decisions of planners on the evolution of a city. Note that the identification of decisions that lead to an improvement – if not the greatest improvement – requires the assumption that the effects of decisions are predictable, at least in the short term (Allen, 2012, p. 83).

Expressing the goal of not only showing the impact of single decisions but of many decisions leads to the notion of capturing decision spaces. To reflect the size of these decision spaces, the optimization method should be flexible in terms of problem formulation and change of input data. Furthermore, in order to disrupt the human thought process accompanying the making of decisions as little as possible, the method should generate solutions very quickly.

In conclusion, a computational method for decision support in urban planning should:

- be value-driven and generate alternatives,
- allow to depict trade-offs between objectives by generating Pareto-optimal solutions,

- allow to identify optimal decisions by showing their impact on the evolution of a city,
- be robust in the sense that it can be applied to a variety of combinations of input parameters,
- return results as fast as possible.

Several classes of optimization algorithms exist which differ by e.g. speed, robustness in terms of numeric starting conditions, permissible mathematical formulations, or if finding the global optimum is guaranteed (Reeves, 1993; Floudas, 1995; Branke, 2008; Bierlaire, 2015).

An optimization method meeting the above stated requirements is multi-parametric Mixed Integer Linear Programming (mpMILP), where the values for decision variables are decided by the algorithm depending on parametrized constraints (Gal, 1995; Pistikopoulos et al., 2007; Liu et al., 2011). These constraints can, but do not necessarily, represent conflicting objectives, which thus implies the ϵ-constraint method (Haimes et al., 1971). For this method all but one objective of a multi-objective optimization problem are converted into constraints. By varying the parameters of those constraints, i.e. the epsilons, Pareto-optimal solutions are identified.

Sampling techniques can then be used to vary any parameter systematically in order to capture the decision space with its exterior bounds and interior stable regions and tipping "points" at which the system design would change in dependence on the decisions of the human user (Cajot et al., 2018; Saleh and Al-Hagla, 2012).

2.3 Mathematical formulation of mpMILP problem

This section states the general formulation of a mpMILP problem and shows how it can be interpreted in the context of urban planning: decisions are usually taken based on performance indicators $\mathit{\Pi}$

$$\mathit{\Pi} = F(\boldsymbol{\phi}), \quad \boldsymbol{\phi} \in \mathit{\Phi} \tag{2.1}$$

$\boldsymbol{\phi}$ denotes denotes all variables whose values are to be decided (i.e. decision variables) within their regarding variable space $\mathit{\Phi}$. As (i) the number of decisions is very large, (ii) these decisions are made by different actors at different phases of the urban development project, and (iii) all these decisions potentially influence the final values of the performance indicators, the decisions are separated into decisions θ, which are typically decided by planners at early phases and larger scales of the urban project, and decision variables $\boldsymbol{\rho}$ and $\boldsymbol{\zeta}$, which are typically decided by different actors at later phases and smaller scales. In the field of multi-level optimization (Floudas, 2000; Pistikopoulos et al., 2007), these other actors are referred to as followers. In the context of urban planning this denotation merely refers to the chronology of decisions and not to the hierarchy of actors.

$$\Pi = f(\theta, \boldsymbol{\rho}, \boldsymbol{\zeta}), \quad \theta \in \Theta, \boldsymbol{\rho} \in \mathbb{R}, \boldsymbol{\zeta} \in \mathbb{Z} \tag{2.2}$$

Here $\boldsymbol{\rho}$ denotes continuous variables and $\boldsymbol{\zeta}$ denotes discrete (i.e. binary or integer) variables. They are decided by an optimization algorithm which solves the following multi-parametric Mixed-Integer Linear Programming problem:

$$\begin{aligned} \min_{\rho,\zeta} \quad & f(\theta, \boldsymbol{\rho}, \boldsymbol{\zeta}) = c_\rho^T(\theta) \cdot \boldsymbol{\rho} + c_\zeta^T(\theta) \cdot \boldsymbol{\zeta} \\ \text{subject to} \quad & V_\rho(\theta) \cdot \boldsymbol{\rho} + V_\zeta(\theta) \cdot \boldsymbol{\zeta} = v(\theta) \\ & W_\rho(\theta) \cdot \boldsymbol{\rho} + W_\zeta(\theta) \cdot \boldsymbol{\zeta} \leq w(\theta) \\ & \theta \in \Theta, \boldsymbol{\rho} \in \mathbb{R}_{\geq 0}, \boldsymbol{\zeta} \in \mathbb{Z} \end{aligned} \tag{2.3}$$

where optimal values for $\boldsymbol{\rho}$ and $\boldsymbol{\zeta}$ are determined in dependence on the values of θ. $\boldsymbol{\rho}$ and $\boldsymbol{\zeta}$ can thus be interpreted as rational reactions of the followers to the decisions of the planners θ. In this work the problem of the followers (2.3) is solved using the standard algorithm for solving Mixed-Integer Linear Programming problems that is implemented in CPLEX (CPLEX 2014), while the problem of the planners (2.2) is explored via sampling of the decision space. This means that the values of decisions of the planners θ are changed according to either systematic sampling or a Sobol sequence (Cajot et al., 2018) and the resulting values for decision variables of the followers $\boldsymbol{\rho}$ and $\boldsymbol{\zeta}$ as well as the values of the performance indicators Π are captured.

Consequently, the stated mpMILP problem is not solved since the goal is not necessarily to capture the entire decision space for every problem instance but rather to probe it until the human has gathered enough insight to identify further questions of interest and to trigger the formulation of a next optimization problem in the interactive optimization approach described by Cajot, (2018).

2.4 Relation between multi-parametric formulation and optimization model

The variables and parameters presented in chapter 3 take the following roles in formulation (2.3): core (i.e. not derived by equality constraints) discrete decision variables $\boldsymbol{\zeta}$ for the optimization model are the number of floors of buildings $\boldsymbol{n}_{\mathbf{fl}}$ (3.1), the existence $\boldsymbol{\xi}$ of buildings (3.3)–(3.4), parks (3.15)–(3.17), and energy conversion technologies (3.41)–(3.42) at specific locations, the energy state of buildings (3.5), and the connection of blocks of buildings to a local energy network (3.44). In addition, auxiliary variables are required for piecewise linearized functions as e.g. $\boldsymbol{\lambda}$ for the sky dome model (3.38)–(3.40). Core continuous decision variables $\boldsymbol{\rho}$ are the operation rates of technologies (3.35)–(3.36).

Although the planner could in principle adjust the values of all parameters, the main parameters are those that parametrize constraints by specifying minimum or maximum accepted bounds for performance indicators. A small example: the actual computed value of the share of RES $\boldsymbol{s}_{\mathbf{res}}$ is a performance indicator, while the specification of a minimum threshold on this indicator $s_{\mathrm{res,min}}$ is a decision of the user, and the values for the decision variables of the model are determined by the algorithm in such a way that their combination does not violate the constraints on some performance indicators while optimizing others. Since the model formulation contains integers, those parametric constraints should often be formulated as inequality constraints and not as equality constraints since the latter would aggravate the convergence of the solver, or even prevent finding feasible solutions. The way a constraint should be formulated, i.e. as a lower or upper bound, depends on the problem at hand and the underlying trade-offs. The description of the developed mpMILP model is the subject of the following chapter.

Chapter 3

Optimization model

Highlights

- MILP model integrating many domains and scales of urban systems
- Concept to quantify the view on landmarks for buildings and districts
- Integration of solar irradiation based on cumulative skies into a MILP model
- MILP model for new and existing buildings, including their energy standard
- Model capturing the influences of the surroundings of parks on their attractiveness

Parts of the content of this chapter were published in (Schüler et al., 2018b) and (Schüler and Cajot, 2018a).

In this chapter it is demonstrated how various domains and scales of urban systems can be captured by a MILP model [1]. Although in the European context, urban renewal projects (so called "brownfield projects") are outnumbering urban expansion projects (so called "greenfield projects"), the model was developed taking also into account the decisions to be made in the scope of greenfield projects. Aiming for a truly versatile applicability of the model, the main reason for this was the perception that from a mathematical point of view, brownfield problems can be regarded as a subset of greenfield problems where some of the decision variables are fixed prior to the optimization.

The selection of urban domains and scales to be covered by the model is justified in sections 1.2.1 and 1.2.3. Figures 1.1 and 1.3 depict the considered domains and scales, respectively. This chapter is structured by ordering the model equations according to the

[1] The optimization model is implemented in AMPL (Fourer, 2014).

domain they belong to, and the spatial scale they occur on. However, such a separation is of course subjective to some extent, as some aspects of urban systems span several domains and/or scales while other aspects arise only from the holistic view of the separate domains and scales.[2]

3.1 Urban form and function

3.1.1 Number of floors and occupancy type

In order to process a planning site with the developed model, this site has to be divided into parcels *pc*. Each of these parcels is assumed to host a building of a specific building type *bt* and the buildings comprise a number of floors $\boldsymbol{n}_{\mathbf{fl}}$ of a specific occupancy type *ot*:

$$\boldsymbol{n}_{\mathbf{fl}}^{pc,bt,ot} \in \mathbb{N}^0 \tag{3.1}$$

3

Occupancy types can take values like "residential" (rsd), "office" (off), "commercial" (com), or "educational" (edu).

In case of a brownfield planning project following optional equation can assure that existing buildings are not replaced with smaller buildings and that occupancy types are preserved:

$$\sum_{bt} \boldsymbol{n}_{\mathbf{fl}}^{pc,bt,ot} \geq n_{\text{fl,min}}^{pc,ot} \quad \forall\, pc \in PC, ot \in OT \tag{3.2}$$

3.1.2 Building type

Considering different building types allows to account for the differences between for example mixed-use buildings (mix) and single family houses (sfh) in e.g. footprint, occupation rates or surface specific energy demand. Binary decision variables indicate if a parcel is occupied either by one specific building type $\boldsymbol{\xi}_{\mathbf{blg}}$ or by a park $\boldsymbol{\xi}_{\mathbf{park}}$:

$$\sum_{bt} \boldsymbol{\xi}_{\mathbf{blg}}^{pc,bt} + \boldsymbol{\xi}_{\mathbf{park}}^{pc} \leq 1 \quad \forall\, pc \in PC \tag{3.3}$$

[2]For an explanation of the notation and convention regarding formulas and symbols see the nomenclature section (page **??**).

A building's existence is coupled to the number of floors via:

$$\frac{\sum_{ot} \boldsymbol{n}_{\mathbf{fl}}^{pc,bt,ot}}{n_{\text{fl,max}}^{pc,bt}} \leq \boldsymbol{\xi}_{\mathbf{blg}}^{pc,bt} \leq \sum_{ot} \boldsymbol{n}_{\mathbf{fl}}^{pc,bt,ot} \quad \forall\, pc \in PC, bt \in BT \tag{3.4}$$

Special constraints for building types can enforce e.g. only residential floors for single family houses (SFH).

3.1.3 Energy state

Buildings have a certain state which indicate their energy demand. An existing building can either be left unrefurbished (unrfb), with potentially measured or otherwise estimated demands (see chapter 4), or it can be refurbished to a specific energy standard es. A new building will be enforced to comply to an energy standard due to building regulations. Thus the state unrfb is not foreseen for new buildings. If a building exists it must have exactly one energy state $\boldsymbol{\xi}_{\mathbf{es}}$:

$$\sum_{es} \boldsymbol{\xi}_{\mathbf{es}}^{pc,es} = \sum_{bt} \boldsymbol{\xi}_{\mathbf{blg}}^{pc,bt} \quad \forall\, pc \in PC \tag{3.5}$$

3

Depending on the local legislation, the refurbishment of landmarked buildings can be prohibited:

$$\boldsymbol{\xi}_{\mathbf{es}}^{pc,es} = 0 \quad \forall\, pc \in PC_{\text{lm}}, es \in ES \setminus \{\text{unrfb}\} \tag{3.6}$$

3.1.4 Gross floor area

The gross floor area (GFA) of a building is indexed over parcels, energy standard, building type, and occupancy type since all of those properties have an effect on e.g. occupants or energy demand. The parameter $A_{\text{fl,exst}}$ designates the GFA of an existing building and the continuous decision variable $\boldsymbol{A}_{\mathbf{fl}}$ designates either the GFA of a new building or the GFA of additionally built floors on top of an existing building. The total GFA per building depends on its number of floors and its footprint A_{fp}:

$$\begin{aligned}&\sum_{es} \boldsymbol{\xi}_{\mathbf{es}}^{pc,es} \cdot A_{\text{fl,exst}}^{pc,ot} + \sum_{es2} \boldsymbol{A}_{\mathbf{fl}}^{pc,es2,bt,ot} = \boldsymbol{n}_{\mathbf{fl}}^{pc,bt,ot} \cdot A_{\text{fp}}^{pc,bt},\\ &es2 \in ES \setminus \{\text{unrfb}\} \quad \forall\, pc \in PC, bt \in BT, ot \in OT\end{aligned} \tag{3.7}$$

Furthermore, the GFA is coupled to the energy standard of a building via:

$$\sum_{bt,ot} \boldsymbol{A}_{\mathbf{fl}}^{pc,es,bt,ot} \leq \boldsymbol{\xi}_{\mathbf{es}}^{pc,es} \cdot \max_{\mathrm{bt}} \left(A_{\mathrm{fp}}^{pc,bt} \cdot n_{\mathrm{fl,max}}^{pc,bt} \right) \qquad \forall\, pc \in PC, es \in ES \setminus \{\mathrm{unrfb}\} \tag{3.8}$$

where the maximum number of floors $n_{\mathrm{fl,max}}$ can be derived from the maximum building height as stated in the following paragraph , equations (3.12) and (3.11).

An optional constraint can serve to forbid the construction of new floors on landmarked buildings:

$$\boldsymbol{A}_{\mathbf{fl}}^{pc,es,bt,ot} = 0 \quad \forall\, pc \in PC_{\mathrm{lm}}, es \in ES \setminus \{\mathrm{unrfb}\}, bt \in BT, ot \in OT \tag{3.9}$$

3.1.5 Height

The building height $\boldsymbol{h}_{\mathbf{blg}}$ is resulting from the height of a potentially existing building $h_{\mathrm{blg,exst}}$ plus the number and building type-dependent height of new or additional floors h_{fl}:

$$\boldsymbol{h}_{\mathbf{blg}}^{pc} = h_{\mathrm{blg,exst}}^{pc} \cdot \sum_{es} \boldsymbol{\xi}_{\mathbf{es}}^{pc,es} + \frac{h_{\mathrm{fl}}^{bt}}{A_{\mathrm{fp}}^{pc,bt}} \cdot \sum_{es,ot} \boldsymbol{A}_{\mathbf{fl}}^{pc,es,bt,ot} \quad \forall\, pc \in PC, bt \in BT \tag{3.10}$$

Both the height of new buildings and the increasing of existing buildings has to respect potential building height limitations $h_{\mathrm{blg,max}}$. These might result on the one hand from site-specific legislations. On the other hand this parameter can serve to prevent buildings from exceeding a height that is typical for their according building type. However, existing buildings can in some circumstances exceed such building height limitations. Thus a maximum permissible building height is implemented indirectly by an upper limit on the number of floors $n_{\mathrm{fl,max}}$:

$$\sum_{ot} \boldsymbol{n}_{\mathbf{fl}}^{pc,bt,ot} \leq n_{\mathrm{fl,max}}^{pc,bt} \qquad \forall\, pc \in PC, bt \in BT \tag{3.11}$$

$$n_{\mathrm{fl,max}}^{pc,bt} = \max \left(n_{\mathrm{fl,exst}}^{pc}, n_{\mathrm{fl,exst}}^{pc} + \left\lfloor \frac{h_{\mathrm{blg,max}}^{bt} - h_{\mathrm{blg,exst}}^{pc}}{h_{\mathrm{fl}}^{bt}} \right\rfloor \right) \qquad \forall\, pc \in PC, bt \in BT \tag{3.12}$$

This accounts for the fact that the height of floors of existing buildings might deviate from typical floor heights for a building type, which in turn affects the permissible number of additional floors on top of the existing floors $n_{\mathrm{fl,exst}}$.

3.1.6 Floor area shares

The shares of gross floor area $\boldsymbol{s}_{\mathbf{gfa}}$ of the different occupancy types are used as a measure for mixed development.

$$\boldsymbol{s}_{\mathbf{gfa}}^{ot1} = \frac{\sum_{pc,bt} \boldsymbol{A}_{\mathbf{fl}}^{pc,bt,ot1}}{\sum_{pc,bt,ot2} \boldsymbol{A}_{\mathbf{fl}}^{pc,bt,ot2}} \quad \forall\, ot1 \in OT \tag{3.13}$$

3.1.7 Standard distance of buildings

The standard distance $\boldsymbol{d}_{\mathbf{std}}$ is a measure from spatial statistics that indicates the degree to which features are scattered around their geometric mean center $(\bar{x}, \bar{y})$. The standard distance of buildings in a neighborhood can be calculated from the locations (x, y) of all buildings via:

$$\boldsymbol{d}_{\mathbf{std}} = \sqrt{\frac{\sum_{pc} \left(x^{pc} - \bar{x}\right)^2}{\sum_{pc} \boldsymbol{\xi}_{\mathbf{blg}}^{pc}} + \frac{\sum_{pc} \left(y^{pc} - \bar{y}\right)^2}{\sum_{pc} \boldsymbol{\xi}_{\mathbf{blg}}^{pc}}} \tag{3.14}$$

3

3.2 Society

3.2.1 Parks

Several authors covered the optimal allocation of parks on the city scale considering aspects like population density, air and water quality, noise, the urban heat island effect, or land use patterns (Neema and Ohgai, 2010; Yuan et al., 2011; Neema and Ohgai, 2013; F.J. Fernández et al., 2015). Assessments on the district to neighborhood scale treat for example the accessibility, connectivity, costs, number of beneficiaries or population density, respectively (Sefair et al., 2012; Yu et al., 2014). This work focuses on the relationships between parks and their surroundings on the building to floor scale. The modeled aspects are inspired by the work of Jacobs, (1961), who described several basic principles characterizing parks with a positive contribution to their environment.

Coherence

Firstly, parks should be enclosed and clearly delimited by a certain number of buildings, rather than isolated at the border of the community (Jacobs, 1961, p. 103 ff.). Not only does a proper enclosure by buildings visually and spatially define the park as a positive feature, but it also increases its accessibility. This is implemented by providing a constraint on occupied parcels around parks:

$$\boldsymbol{\xi}_{\mathbf{park}}^{pc1} \leq \frac{\sum_{pc2,bt} \boldsymbol{\xi}_{\mathbf{blg}}^{pc2,bt}}{n_{\text{blg@parks,min}}} \quad \forall \{pc1, pc2 \in PC : pc1 \neq pc2, d_{\text{ecl}}^{pc1,pc2} \leq d_{\text{blg@parks,max}}\} \tag{3.15}$$

By adjusting the minimum number of buildings around a park $n_{\text{blg@park,min}}$ implications of this constraint can be influenced. Higher numbers result to more enclosed parks. Setting the maximum euclidean distance between the park's parcel and surrounding parcels $d_{\text{blg@parks,max}}$ defines the perimeter in which surrounding buildings should be considered. Different combinations of both parameters allow to either enforce or prohibit specific layouts such as parks located at corners of blocks.

Diversity

Secondly, and related to the enclosure principle, surrounding buildings should offer a high diversity of uses (Jacobs, 1961, p. 103). This in turns ensures a high diversity of users, leading to a more continuous occupation of the park throughout the day, thus reducing insecurity and vandalism (Jacobs, 1961, p. 95). This can be enforced by putting thresholds on numbers of floors of a certain occupancy type on parcels around parks $n_{\text{fl@park,min}}$:

$$\boldsymbol{\xi}_{\mathbf{park}}^{pc1} \leq \frac{\sum_{pc2,bt} \boldsymbol{n}_{\mathbf{fl}}^{pc2,bt}}{n_{\text{fl@park,min}}^{bt}} \quad \forall \{pc1, pc2 \in PC : pc1 \neq pc2, d_{\text{ecl}}^{pc1,pc2} \leq d_{\text{blg@parks,max}}\} \tag{3.16}$$

Direct sunlight

Thirdly, the attractiveness of the park is also influenced by the amount of direct sunlight $\boldsymbol{ir}_{\mathbf{dir}}$ throughout the year. Complete obstruction of sunlight by tall buildings should be avoided (Jacobs, 1961, p. 103, 105f.). The constraint for a minimum of direct solar irradiation per surface $ir_{\text{dir,min}}$ is (see page 51):

$$\boldsymbol{ir}_{\mathbf{dir}}^{pc} \geq ir_{\text{dir,min}} \cdot \boldsymbol{\xi}_{\mathbf{park}}^{pc} \quad \forall\, pc \in PC \tag{3.17}$$

Landmark view

See section 3.2.4.

3.2.2 Density

A common planning measure on aggregated scales are densities of different kinds, such as surface densities or population densities. In this work surface densities are employed which can be converted into population densities, once statistical occupation rates are known:

Floor Area Ratio

The Floor Area Ratio $\boldsymbol{FAR}$ is the gross floor area $\boldsymbol{A}_{\mathbf{fl}}$ of all buildings divided by the area of the considered parcels A_{pc} of the entire neighborhood:

$$\boldsymbol{FAR} = \frac{\sum_{pc,bt,ot} \boldsymbol{A}_{\mathbf{fl}}^{pc,bt,ot}}{\sum_{pc} A_{\text{pc}}^{pc}} \tag{3.18}$$

Building Area Ratio

The Building Area Ratio $\boldsymbol{BAR}$ (or site coverage ratio) is defined as the sum of footprint areas of all buildings divided by the area of the considered parcels of the entire neighborhood:

$$\boldsymbol{BAR} = \frac{\sum_{pc,bt} \boldsymbol{\xi}^{pc,bt} \cdot A_{\text{fp}}^{bt}}{\sum_{pc} A_{\text{pc}}^{pc}} \tag{3.19}$$

3.2.3 Proximity

Shops

The share of commercial gross floor area, as defined on page 43, allows to scale the amount of shops with residential density. However, it does not allow to influence the spatial distribution of shops. A more evenly distribution of shops could be desirable since locating shops within certain distances could help to promote soft mobility. This is implemented by setting a lower bound on the number of commercial floors $n_{\text{fl,com,min}}$ within a maximum distance $d_{\text{com,max}}$ around buildings which can have residential floors:

$$\sum_{pc2,bt} \boldsymbol{n}_{\mathbf{fl}}^{pc2,bt,\text{com}} \geq n_{\text{fl,com,min}} \cdot \sum_{bt} \boldsymbol{\xi}_{\mathbf{blg}}^{pc1,bt} \quad \forall \{pc1, pc2 \in PC : d_{\text{mnh}}^{pc1,pc2} \leq d_{\text{com,max}}\} \tag{3.20}$$

d_{mnh} is the Manhattan distance as displayed in figure 3.1 (Black, 2006). Specifying more than one commercial floor within the certain distance could help to ensure the provision

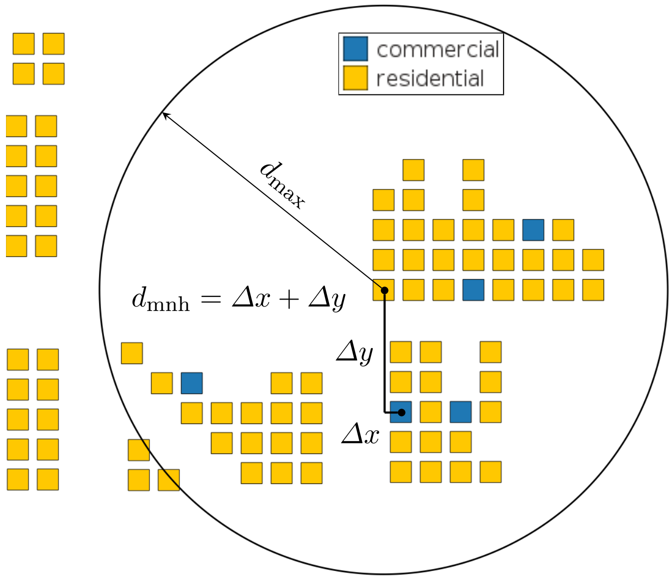


Figure 3.1 – Calculation of Manhattan distance

with shops of different kinds. The combination of shop-to-residence ratio and number of shops within a maximum distance allow to influence quantity and distribution of shops.

Parks

Most of the points just stated for shops also hold for parks resulting in a similar constraint:

$$\sum_{pc2} \boldsymbol{\xi}^{pc2}_{\mathbf{park}} \geq n_{\text{parks,min}} \cdot \sum_{bt} \boldsymbol{\xi}^{pc1,bt}_{\mathbf{blg}} \quad \forall \{pc1, pc2 \in PC : pc1 \neq pc2, d^{pc1,pc2}_{\text{mnh}} \leq d_{\text{park,max}}\} \tag{3.21}$$

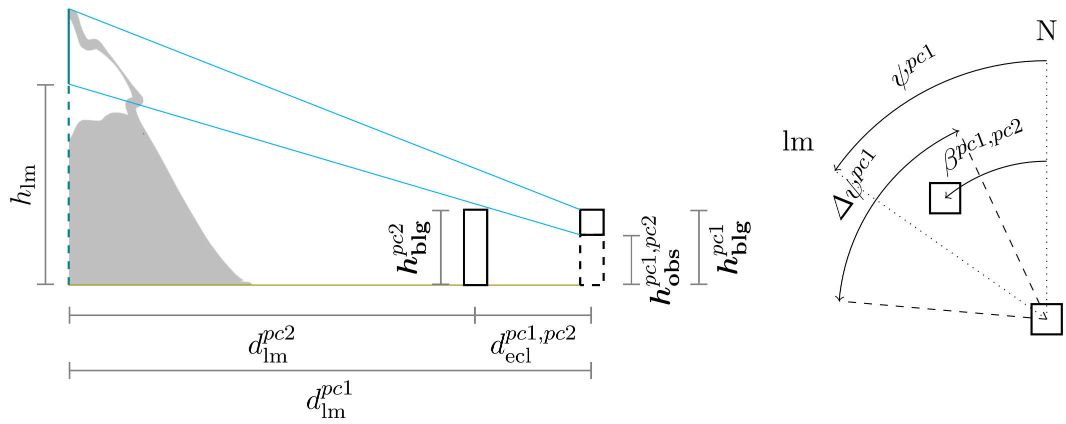
It shall be hinted that the proximity of parks is not the same as the coherence of a park as defined on page 43, since a park could be embedded within many buildings while still being not close to all buildings in the neighborhood. Proximity constraints for shops and parks influence implicitly also positively the diversity of functions within a neighborhood.

3.2.4 Landmark view

Private view

The quality of living space and with it its cost is influenced by the view it offers on surrounding landmarks (Benson et al., 1998; Thalmann, 2010). In recognition of the demand for computer tools that inform planners, architects, and building contractors, a few previous attempts exist to visualize or quantify the view in computer models. The Ladybug plug-in for Grasshopper developed by Roudsari et al., (2013a) allows to vizualize the obstruction to views from specified locations within a given urban scene by means of view roses. Ferreira et al., (2015) calculate the visibility of landmarks by rendering urban scenes from sampling points distributed over the landmark and determining buildings from which these points could be seen. The results can then be plotted by coloring the buildings that enjoy a view on the landmark. Their number serves further as an indicator to compare urban development plans. In addition they are designed to analyze extrinsically defined scenes where the here proposed model considers urban form intrinsically.

The here proposed method allows to quantify the view both per building and per neighborhood. It is further not limited to analyze extrinsically defined scenes, but by considering urban form intrinsically, change the latter to optimize or constrain the view.



(a) Side view **(b)** Top view

Figure 3.2 – Views of a planning site to illustrate considered heights, distances and angles for the calculation of the LVF

Consequently a performance indicator to assess view quality is needed: The Landmark View Factor (LVF) is defined as the share of floors, either per building or per neighborhood, that have a view on a specified landmark. The number of floors with a view per building can be approximated by calculating the vertical part of a building from which the landmark could be seen and dividing it by the average floor height (see figure 3.2a). This number is calculated for each pair of buildings $\boldsymbol{n}_{\mathbf{fl,view,rel}}$, where one is potentially obstructing the view of the other:

$$\boldsymbol{n}^{pc1,pc2}_{\mathbf{fl,view,rel}} = \frac{\boldsymbol{h}^{pc1}_{\mathbf{blg}} - \boldsymbol{h}^{pc1,pc2}_{\mathbf{obs}}}{\bar{h}_{\mathrm{fl}}} \quad \forall\{pc1, pc2 \in PC : \\ pc1 \neq pc2, \psi^{pc1} - \frac{\Delta\psi^{pc1}}{2} \leq \beta^{pc1,pc2} \leq \psi^{pc1} + \frac{\Delta\psi^{pc1}}{2} \wedge d^{pc1,pc2}_{\mathrm{ecl}} \leq d^{pc1,pc2}_{\max}\} \tag{3.22}$$

h_{obs} is the height of the obstructed part of the building due to building 2, $\overline{h}_{\text{fl}}$ is an average floor height. ψ is the angle from north towards the direction of the landmark, and β is the angle from north towards the direction of the potentially obstructing building. The height of the obstructed part of the building can be deduced from the height of the landmark h_{lm}, the elevation of the landmark z_{lm}, the distance towards the landmark d_{lm}, the elevation of buildings z_{blg} and the euclidean distance between the two considered buildings d_{ecl} using the intercept theorem (figure 3.2a):

$$\frac{\left(\boldsymbol{h}_{\textbf{blg}}^{pc2} + z_{\text{blg}}^{pc2}\right) - \left(\boldsymbol{h}_{\textbf{obs}}^{pc1,pc2} + z_{\text{blg}}^{pc1}\right)}{\left(h_{\text{lm}} + z_{\text{lm}}\right) - \left(\boldsymbol{h}_{\textbf{obs}}^{pc1,pc2} + z_{\text{blg}}^{pc1}\right)} = \frac{d_{\text{ecl}}^{pc1,pc2}}{d_{\text{lm}}^{pc1}} \tag{3.23}$$

Using the euclidean distance between centers of parcels disregards the horizontal extension of the buildings, which results in an optimistic estimation of the LVF of all buildings and in neglecting the more obstructing effect of buildings with larger footprints. A conservative estimation could be made when using the distances between parcel borders. However, an accurate assessment of the final LVF in an early planning phase is already hindered as the planner might not be able to influence the final buildings' extension and location on each parcel. Thus this indicator should rather serve to detect general trends and trade-offs with other urban aspects (deVries et al., 2005).

The number of floors that enjoy a good view is defined for every pair of parcels where a building on one of it could potentially obstruct the view of the other. This is accounted for by regarding only parcels that are both within a maximum distance $d_{\max}$ and a certain view range towards the landmark $\Delta\psi$ (see figure 3.2b). The maximum distance is again deduced from the intercept theorem by setting $\boldsymbol{h}_{\textbf{blg}}^{pc2} = h_{\text{blg,max}}^{pc2}$ and $\boldsymbol{h}_{\textbf{obs}}^{pc1} = 0$ in (3.23) and resolving for $d_{\text{ecl}}^{pc1,pc2}$:

$$d_{\max}^{pc1,pc2} = d_{\text{lm}}^{pc2} \cdot \frac{h_{\text{blg,max}}^{pc2} + z_{\text{blg}}^{pc2} - z_{\text{blg}}^{pc1}}{h_{\text{lm}} + z_{\text{lm}} - \left(h_{\text{blg,max}}^{pc2} + z_{\text{blg}}^{pc2}\right)} \tag{3.24}$$

with the maximum height over all building types $\max_{bt \in BT} h_{\text{blg,max}}^{bt}$.

The view range $\Delta\psi$ can be deduced from the distance towards the landmark and the radius of the landmark r_{lm} which shall be visible:

$$\Delta\psi^{pc1} = 2 \cdot \arctan \frac{r_{\text{lm}}}{d_{\text{lm}}^{pc1}} \tag{3.25}$$

The radius depends naturally on the type of landmark. In the case of a natural land mark such as a mountain range, most likely only a broader view range would be considered as providing a building with a nice view than it would be the case with e.g. an architectural landmark. The view range has further an effect on the number of generated constraints for the model as a larger view range leads to more constraints.

To finally get the actual number of floors with a nice view $\boldsymbol{n}_{\mathbf{fl,view}}$ for each building requires taking the minimum[3] of (3.22).

$$\boldsymbol{n}^{pc1}_{\mathbf{fl,view}} = \min_{\text{pc2}}\{\boldsymbol{n}^{pc1,pc2}_{\mathbf{fl,view,rel}}; \sum_{bt,ot} \boldsymbol{n}_{\mathrm{fl}}{}^{pc1,bt,ot}\} \quad \forall\, pc1 \in PC \tag{3.26}$$

The landmark view factor $\boldsymbol{LVF}$ per building is then

$$\boldsymbol{LVF}^{pc} = \frac{\boldsymbol{n}^{pc}_{\mathbf{fl,view}}}{\sum_{bt,ot} \boldsymbol{n}^{pc,bt,ot}_{\mathbf{fl}}} \quad \forall\, pc \in PC \tag{3.27}$$

In order to compare resulting neighborhood layouts, the overall $\boldsymbol{LVF}_{\mathbf{tot}}$ is calculated. Therefore the LVFs of all buildings are summed up and normalized by the total number of floors within the neighborhood:

$$\boldsymbol{LVF}_{\mathbf{tot}} = \frac{\sum_{pc} \boldsymbol{n}^{pc}_{\mathbf{fl,view}}}{\sum_{pc,bt,ot} \boldsymbol{n}^{pc,bt,ot}_{\mathbf{fl}}} \tag{3.28}$$

Public view

A view from many floors on a landmark is a desirable target, but this view is not enjoyable by everyone, if the buildings are not used for public purposes. The quality of a new neighborhood might, however, also be assessed by the question from how many public spaces a landmark is visible. The above introduced concept is thus extended by an LVF from open spaces. Therefore a binary variable $\boldsymbol{\xi}_{\mathbf{park,view}}$ is used to indicate if an open space, e.g. a public park, has a view on a landmark and if the open space is used for public purposes (e.g. parks)[4]:

$$\boldsymbol{\xi}^{pc1}_{\mathbf{park,view}} = \min_{\text{pc2}}\{\boldsymbol{n}^{pc1,pc2}_{\mathbf{fl,view,rel}}; \boldsymbol{\xi}^{pc1}_{\mathbf{park}}\} \quad \forall\, pc1 \in PC \tag{3.29}$$

The overall LVF of a neighborhood for view from parks $\boldsymbol{LVF}_{\mathbf{parks,tot}}$ is then defined as the share of parks from which the landmark can be seen:

$$\boldsymbol{LVF}_{\mathbf{parks,tot}} = \frac{\sum_{pc} \boldsymbol{\xi}^{pc}_{\mathbf{park,view}}}{\sum_{pc} \boldsymbol{\xi}^{pc}_{\mathbf{park}}} \tag{3.30}$$

[3] A linear form of (3.26) is implemented using inequality constraints.
[4] A linear form of (3.29) is implemented using inequality constraints.

3.3 Energy

3.3.1 Energy demand

The calculation of the energy demand depends on the energy state of a building section 3.1.3. For existing buildings ideally some measured demands are available. Otherwise e.g. statistical or simulation models can be used to estimate those demands $e_{\text{blg,exst}}$ (chapter 4). For the construction of new buildings or new floors on top of existing buildings, or for the refurbishment of existing buildings, national standards and regulations define energy target values. In the case of some Swiss norms, the target values for refurbished buildings are sometimes expressed as a multiple of the target value for new buildings rf. Surface-specific energy demands e_{blg} specified by those norms, are used to estimate building demands $\boldsymbol{E}_{\mathbf{blg}}$.

$$\begin{aligned}\boldsymbol{E}_{\mathbf{blg}}^{ue,pc,t} = \sum_{es,ot} e_{\text{blg}}^{ue,es,ot,t} \cdot \left(\sum_{bt} sr_{\text{era}}^{bt} \cdot \boldsymbol{A}_{\mathbf{fl}}^{pc,es,bt,ot} + rf \cdot \boldsymbol{\xi}_{\mathbf{es}}^{pc,es} \cdot sr_{\text{era,exst}}^{pc} \cdot A_{\text{fl,exst}}^{pc,ot} \right) \\ + e_{\text{blg,exst}}^{ue,pc} \cdot \boldsymbol{\xi}_{\mathbf{es}}^{pc,\text{unrfb}} \cdot sr_{\text{era,exst}}^{pc} \cdot A_{\text{fl,exst}}^{pc,ot}, \\ es \in ES \setminus \{\text{unrfb}\} \quad \forall\, ue \in UE \setminus \{\text{dhw}, \text{elec}\}, pc \in PC, t \in T\end{aligned} \tag{3.31}$$

A conversion factor sr_{era} allows the estimation of the energetic reference area (ERA) based on the GFA (3.7). In case of new buildings this factor is building type specific, in case of existing buildings it is location specific. Five types of useful energy (ue) demands are considered in this work: Space heating (sh), space cooling (sc), domestic hot water (dhw), lighting, and services provided by electric appliances (elec). The demands for lighting and electric appliances are expressed in final energy in order to avoid the requirement of modeling the efficiencies of those appliances.

Demands that are independent on the building's energy standard (i.e. domestic hot water and electricity for lighting and electric appliances) are calculated as:

$$\begin{aligned}\boldsymbol{E}_{\mathbf{blg}}^{ue,pc,t} =& e_{\text{blg}}^{ue,ot,t} \cdot \sum_{es,bt,ot} sr_{\text{era}}^{bt} \cdot \boldsymbol{A}_{\mathbf{fl}}^{pc,es,bt,ot} \\ &+ e_{\text{blg,exst}}^{ue,pc} \cdot \sum_{es} \boldsymbol{\xi}_{\mathbf{es}}^{pc,\text{unrfb}} \cdot sr_{\text{era,exst}}^{pc} \cdot A_{\text{fl,exst}}^{pc,ot}, \\ &es \in ES \setminus \{\text{unrfb}\} \quad \forall\, pc \in PC, t \in T \quad \forall\, ue \in \{\text{dhw}, \text{elec}\}, pc \in PC, t \in T\end{aligned} \tag{3.32}$$

3.3.2 Energy supply

The resulting energy demand of each building has to be satisfied by a combination of different conversion technologies CT, which are installed at the building, and energy form-specific exchange technologies XT, which allow to exchange with energy networks. Thus local balances for each energy form, location and time step have to be closed:

$$\boldsymbol{E}_{\mathbf{blg}}^{ue,pc,t} = \sum_{ct} \boldsymbol{E}_{\mathbf{ct}}^{ef,lc,ct,t} + \boldsymbol{E}_{\mathbf{xt}}^{ef,lc,t} \quad \forall\, ue \in UE, ef \in EF, pc \in PC \subseteq LC, lc \in LC, t \in T \tag{3.33}$$

Six final energy forms are considered: heat, cold, electricity, natural gas, fuel oil, and wood pellets. The set of locations LC comprises building parcels, as well as locations of centralized technologies. The energy networks are modeled by energy balances, which allow to exchange energy between buildings, locations of centralized conversion technologies, and national energy networks $\boldsymbol{E}_{\mathbf{ntw,nat}}^{ef,t}$.

$$\sum_{lc} \boldsymbol{E}_{\mathbf{xt,ntw}}^{ef,lc,t} + \boldsymbol{E}_{\mathbf{ntw,nat}}^{ef,t} = 0 \quad \forall\, ef \in EF, t \in T \tag{3.34}$$

Exchange technologies have thus two flows of the same energy form, one contributing to the local energy balance $\boldsymbol{E}_{\mathbf{xt}}$ (3.33) and one contributing to the network balance $\boldsymbol{E}_{\mathbf{xt,ntw}}$ (3.34).

The actual energy flows depend on the operation rate $\boldsymbol{o}$ and a rate-specific energy flow f of each technology. The equation for all energy technologies ET, which comprise the subsets of conversion and exchange technologies, is:

$$\boldsymbol{E}^{ef,lc,et,t} = \boldsymbol{o}^{lc,et,t} \cdot f^{ef,lc,et,t} \quad \forall\, ef \in EF, lc \in LC, et \in ET, t \in T \tag{3.35}$$

The rate-specific energy flow comprises conversion efficiencies (depending on the technology and energy form) or exchange and transport losses. Its sign determines if a flow enters or leaves a balance. The operation rate of each technology is naturally limited by its existence ξ and by its minimum and maximum nominal sizes, $\sigma_{\min}$ and $\sigma_{\max}$:

$$\boldsymbol{\xi}^{lc,et,t} \cdot \min_{s} \sigma_{\min}^{et,s} \leq \boldsymbol{o}^{lc,et,t} \leq \boldsymbol{\xi}^{lc,et,t} \cdot \max_{s} \sigma_{\max}^{et,s} \quad \forall\, lc \in LC, et \in ET, t \in T \tag{3.36}$$

These minimum and maximum nominal sizes can be further indexed over segments s of piecewise linearized cost functions to account for economies of scale (see section 3.5).

PV

For detailed descriptions of each type of conversion technologies the reader is refered to the references stated above. In the following only the model for solar conversion technologies is presented for constituting a novel method that integrates cumulative skies as introduced by Robinson and Stone, (2004) into a MILP formulation.

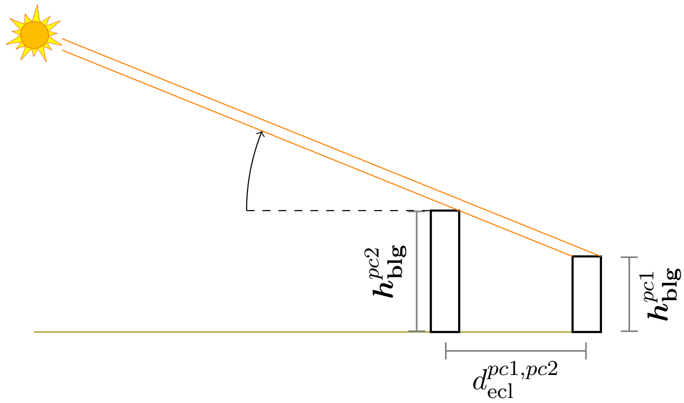


Figure 3.3 – Calculation of obstruction to sun patch

In order to assess the amount of electricity generated by PV panels on the buildings' roofs it is necessary to know the total incident solar irradiation. This depends on the tilt angle and area of the mounted PV panels and on the amount of incident irradiation. The amount of solar irradiation during a specific time period coming from a specific sky patch can be assessed using cumulative skies (see figure 6.7). The incident irradiation on the rooftop then depends on obstructions towards this sky vault. In urban surroundings, near-field obstructions depend mainly on the location and height of surrounding buildings. Thus the problem can be narrowed down to the determination of whether a sky patch can be seen from a given parcel. Therefore it is determined for every parcel and for all azimuth directions of all sky patches, which building in each sky patch direction is obstructing the sky the most by calculating the maximum[5] tangent of elevation angle $\mathbf{tan}\,\boldsymbol{\epsilon}$[6] over all pairs of building heights (compare figure 3.3 and figure 3.2b):

$$\sum_{el} \mathbf{tan}\,\boldsymbol{\epsilon}^{pc1,az,el} = \max_{\mathrm{pc2}} \frac{\left(z^{pc2}_{\mathrm{blg}} + \boldsymbol{h}^{pc2}_{\mathbf{blg}}\right) - \left(z^{pc2}_{\mathrm{blg}} + \boldsymbol{h}^{pc1}_{\mathbf{blg}}\right)}{d^{pc1,pc2}_{\mathrm{ecl}}}$$
$$\forall \left\{ pc1, pc2 \in PC : pc1 \neq pc2, \alpha^{az} - \frac{\Delta\alpha^{az}}{2} \leq \beta^{pc1,pc2} \leq \alpha^{az} + \frac{\Delta\alpha^{az}}{2} \right\} \tag{3.37}$$

where the azimuth angles α and the elevation angles ϵ of all sky patches are indexed over two discrete sets AZ and EL, respectively. Calculating the tangent of the elevation angle instead of the elevation angle itself allows to preserve a linear formulation. Furthermore,

[5] A linear form of (3.37) is implemented using inequality constraints. Note that consequently the values of $\tan\epsilon$ are meaningless for problems where the objective function does not drive these values to their bounds.

[6] Assigning a variable to the tangent of the elevation angle rather than to the angle itself allows to maintain a linear formulation.

there is a tangent variable for each single sky patch in order to calculate the irradiation from the sky dome using a piecewise linear formulation. Therefore for each azimuth direction the highest (partly) obstructed sky patch is determined using binary variables $\boldsymbol{\lambda}$:

$$\boldsymbol{\lambda}^{pc,az,el} \cdot \tan \epsilon^{el}_{\min} \leq \mathbf{tan}\, \boldsymbol{\epsilon}^{pc1,az,el} \leq \boldsymbol{\lambda}^{pc,az,el} \cdot \tan \epsilon^{el}_{\max} \quad \forall\, pc \in PC, az \in AZ, el \in EL \tag{3.38}$$

$$\sum_{el} \boldsymbol{\lambda}^{pc,az,el} = 1 \quad \forall\, pc \in PC, az \in AZ \tag{3.39}$$

The total (i.e., direct and indirect), surface specific irradiation $\boldsymbol{ir}_{\mathbf{tot}}$ for each parcel and each time step is then a function of obstructed sky patches:

$$\boldsymbol{ir}^{pc,t}_{\mathbf{tot}} = ir^{t}_{\text{tot,unobs}} - \sum_{az,el} \left(ir^{az,el,t}_{\text{tot,ic}} \cdot \boldsymbol{\lambda}^{pc,az,el} - ir^{az,el,t}_{\text{tot,gr}} \cdot \mathbf{tan}\, \boldsymbol{\epsilon}^{pc,az,el} \right) \quad \forall\, pc \in PC, t \in T \tag{3.40}$$

with the total irradiation from the unobstructed sky vault $ir_{\text{tot,unobs}}$ and the intercept $ir_{\text{tot,ic}}$ and gradient $ir_{\text{tot,gr}}$ of each sky patch. Herein it is assumed that the amount of irradiation not received from a sky patch is linear proportional to its degree of obstruction. For lower or upper bounds on direct sunlight in parks (see page 44), the sky domes only comprise the amount of direct irradiation.

Finally the upper bound for the electricity output of a roof mounted PV panel with electric efficiency η_{el} is:

$$\boldsymbol{E}^{\text{elec},pc,\text{pv},t} \leq \eta^{\text{pv}}_{\text{el}} \cdot sr_{\text{pv}} \cdot A^{bt}_{\text{fp}} \cdot \left(\boldsymbol{ir}^{pc,t}_{\mathbf{tot}} + ir_{\text{tot,unobs}} \cdot (1 - \boldsymbol{\xi}^{pc,bt}_{\mathbf{blg}}) \right) \quad \forall\, pc \in PC, t \in T \tag{3.41}$$

$$\boldsymbol{E}^{\text{elec},pc,\text{pv},t} \leq \sum_{bt} \boldsymbol{\xi}^{pc,bt}_{\mathbf{blg}} \cdot \eta^{\text{pv}}_{\text{el}} \cdot sr_{\text{pv}} \cdot A^{bt}_{\text{fp}} \cdot ir^{t}_{\text{tot,unobs}} \quad \forall\, pc \in PC, t \in T \tag{3.42}$$

where the panel surface depends on the constructed building's footprint and the share of roof surface available for PV panel installation sr_{pv}. (3.41) assures a panel area chosen according to the building type's footprint while (3.42) prevents panels on empty parcels.

3.3.3 Energy networks

An exchange technology extracts from the neighborhood-wide network the amount required for satisfying the local balance plus an amount to account for transfer losses r_{loss}. Depending on the energy form, this loss can be proportional to both the amount of transfered energy and the network distance between the parcel and the feed-in point of the centralized conversion technologies d_{ntw}. Thus the rate-specific energy flow for an exchange technology is:

$$r_{\text{ntw}}^{lc,xt,t} = 1 + r_{\text{loss}} \cdot d_{\text{ntw}}^{lc} \quad \forall\, lc \in LC, xt \in XT, t \in T \tag{3.43}$$

The distance d_{ntw} is the sum of the network distance on neighborhood scale as explained below and the Manhattan distance (Black, 2006) between the parcel and the point the block is connected to the network.

The network model was developed with the goal of obtaining a good estimation of the network length while increasing the problem size as little as possible. A conventional way to include the network layout in MILP formulations is to decide the existence of connections between nodes using binary variables for each potential connection (Söderman and Pettersson, 2006; Weber, 2008; Fazlollahi, 2014). For larger problems this results into a high amount of binaries. In contrary the method proposed here uses binary variables for the decision of whether a block is connected to a network $\boldsymbol{\xi}_{\mathbf{hn}}^{bl}$.

3

The heat transfer station of a building can be only installed $\boldsymbol{\xi}_{\mathbf{xt,ntw}}^{pc,\text{hts}}$, if a block is connected:

$$\boldsymbol{\xi}_{\mathbf{xt,ntw}}^{pc,\text{hts}} \leq \boldsymbol{\xi}_{\mathbf{hn}}^{bl} \quad \forall\, bl \in BL, pc \in PC^{bl} \tag{3.44}$$

The neighborhood-scale network model is based on the identification of network branches before the actual optimization. Therefore the actual planning site is studied (figure 6.1) and potential network layouts connecting all blocks is designed, where blocks could be connected in different ways. These layouts are then analyzed to identify branches. The main branch is starting at the point where the neighborhood-scale network is connected to a network of an upper scale. Following this branch, at each bifurcation it is checked for each bifurcating pipe if it connects more than one block. If so, an additional branch is defined. Otherwise it is defined as a block connection whose length $l_{\text{ntw,bl}}$ is stored. In the case of several potential block connections of one block the average is taken. The branches are then reviewed to identify and merge pairs of branches that potentially connect the same blocks. Following this, it is determined for each pair of blocks and branches, how long the branch would at least have to be if the block was connected, resulting in the lengths of the branch segments $l_{\text{ntw,seg}}$. Each branch length $\boldsymbol{l}_{\mathbf{ntw,branch}}^{br}$

can then be determined by the following equation:

$$\boldsymbol{l}^{br}_{\mathbf{ntw,branch}} \geq \boldsymbol{\xi}^{bl}_{\mathbf{hn}} \cdot l^{bl,br}_{\mathrm{ntw,seg}} \quad \forall\, br \in BR, bl \in BL \tag{3.45}$$

The total length of a network $\boldsymbol{l}_{\mathbf{ntw}}$ is then:

$$\boldsymbol{l}_{\mathbf{ntw}} = \sum_{br} \boldsymbol{l}^{br}_{\mathbf{ntw,branch}} + \sum_{bl} \boldsymbol{\xi}^{bl}_{\mathbf{hn}} \cdot l^{bl}_{\mathrm{ntw,bl}} \tag{3.46}$$

Connection rate

The connection rate $\boldsymbol{cr}_{\mathbf{ntw}}$ is defined as the share of buildings which is connected to an energy network via an exchange technology:

$$\boldsymbol{cr}_{\mathbf{ntw}} = \frac{\sum_{pc,xt} \boldsymbol{\xi}^{pc,xt}_{\mathbf{xt,ntw}}}{\sum_{pc,bt} \boldsymbol{\xi}^{pc,bt}_{\mathbf{blg}}} \tag{3.47}$$

It is calculated after the optimization to be able to compare resulting plans.

3

3.4 Environment

Being an explicit planning target in many countries and cities (Trutnevyte, 2013; Sperling et al., 2011; Commission, 2014), including in one of the chosen case studies (see section 6.1), the share of energy originating from renewable sources is chosen as main indicator to measure the sustainability of the energy supply system.

3.4.1 Greenhouse gas emissions

The greenhouse gas emissions $\boldsymbol{Em}_{\mathbf{ghg}}$ due to the exchange of energy carriers across the neighborhood boundary are calculated as:

$$\boldsymbol{Em}_{\mathbf{ghg}} = \sum_{ef,t} em^{ef} \cdot \boldsymbol{E}^{ef,t}_{\mathbf{ntw,nat}} \tag{3.48}$$

with an energy-specific emission factor em.

3.4.2 Share of renewable energy sources

The share of energy from renewable energy sources $\boldsymbol{s}_{\mathbf{res}}$ is defined here as the part of the sum of annual energy required to cover the demand of buildings, network losses

$\boldsymbol{E}_{\mathbf{hn,loss}}$, and potential net electricity exports $\boldsymbol{E}_{\mathbf{exp,net}}$ that are covered by renewable energy sources.

The following energy flows are considered as renewable: Heat from wood pellet boilers and heat pumps using heat from the air $\boldsymbol{E}_{\mathbf{air}}$, the ground $\boldsymbol{E}_{\mathbf{soil}}$, or waste heat $\boldsymbol{E}_{\mathbf{wht}}$ from e.g. industrial zones, electricity from PV, and partly from the national electric network $\boldsymbol{E}_{\mathbf{imp,net}}$.

$$\begin{aligned}\boldsymbol{s}_{\mathbf{res}} = \Bigg(& s_{\text{res,en-nat}} \cdot \boldsymbol{E}_{\mathbf{imp,net}} + \sum_t \Bigg(\boldsymbol{E}^{t}_{\mathbf{wht}} \\ & + \sum_{lc} \left(\boldsymbol{E}^{\text{heat},lc,\text{ashp},t}_{\mathbf{air}} + \boldsymbol{E}^{\text{heat},lc,\text{gshp},t}_{\mathbf{soil}} + \boldsymbol{E}^{\text{heat},lc,\text{wood boiler},t} + \boldsymbol{E}^{\text{elec},lc,\text{pv},t} \right) \Bigg) \Bigg) \\ & / \left(\sum_{ue,pc,t} \boldsymbol{E}^{ue,pc,t}_{\mathbf{blg}} + \boldsymbol{E}_{\mathbf{hn,loss}} + \boldsymbol{E}_{\mathbf{en-loc,loss}} + \boldsymbol{E}_{\mathbf{exp,net}} \right)\end{aligned} \tag{3.49}$$

The net exported and imported electricity flows are calculated using the binary method for modeling absolute values in MILP (Rubin, 2012):

$$\boldsymbol{E}_{\mathbf{exp,net}} - \boldsymbol{E}_{\mathbf{imp,net}} = \boldsymbol{E}^{\text{elec}}_{\mathbf{ntw,nat}} \tag{3.50}$$

$$0 \leq \boldsymbol{E}_{\mathbf{exp,net}} \leq \boldsymbol{\xi}_{\mathbf{exp,net}} \cdot E_{\text{exp,max}} \tag{3.51}$$

$$0 \leq \boldsymbol{E}_{\mathbf{imp,net}} \leq (1 - \boldsymbol{\xi}_{\mathbf{exp,net}}) \cdot E_{\text{imp,max}} \tag{3.52}$$

From (3.49) a constraint can be derived to ensure a minimum share of RES $s_{\text{res,min}}$ for the energy supply of the neighborhood.

3.5 Economy

Considered cost factors in this work are: Investment and operation costs of the provision of energy and the investment cost of the transportion network. To account for the effect of economies of scales piecewise linearization is employed for the calculation of the investment cost of technologies .

3.5.1 Energy demand: refurbishment

For the calculation of the costs for the refurbishment of existing buildings $\boldsymbol{C}^{pc}_{\mathbf{refurb}}$, refurbishment measures of different building parts are taken into account: the roof, the base, the facades, and the windows.

$$
\begin{aligned}
\boldsymbol{C}_{\mathbf{refurb}}^{pc} = \sum_{es,bt} \boldsymbol{\xi}_{\mathbf{es}}^{pc,es} \cdot \Big(& c_{\text{rfb,cst}}^{bt} \\
& + c_{\text{rfb,roof}}^{es,bt} \cdot A_{\text{fp}}^{pc,bt} \\
& + c_{\text{rfb,base}}^{es,bt} \cdot A_{\text{fp}}^{pc,bt} \\
& + c_{\text{rfb,fcd}}^{es,bt} \cdot w_{\text{fcd}}^{pc,bt} \cdot h_{\text{blg,exst}}^{pc} \cdot \left(1 - gr^{pc,bt}\right) \\
& + c_{\text{rfb,wdw}}^{es,bt} \cdot w_{\text{fcd}}^{pc,bt} \cdot h_{\text{blg,exst}}^{pc} \cdot gr^{pc,bt} \Big), \\
& es \in ES \setminus \{\text{unrfb}\} \quad \forall \left\{ pc \in PC : h_{\text{blg,exst}}^{pc} > 0 \right\}
\end{aligned}
\tag{3.53}
$$

A constant cost factor $c_{\text{rfb,cst}}$ accounts for the planning costs and depends only on the building type. The costs for the refurbishment of roof $c_{\text{rfb,roof}}$ and base $c_{\text{rfb,base}}$ depend on the building's footprint, while the costs for the refurbishment of facades $c_{\text{rfb,fcd}}$ and windows $c_{\text{rfb,wdw}}$ depend on the glazing ratio gr and the facade surface. The latter is approximated with the product of building height and the total width of all facades of a building w_{fcd}.

3

3.5.2 Energy supply

The operation rates of the technologies for each time step (3.36) result from closing the energy balances (3.33) (section 3.3). The final size of the technology that shall be purchased, results from the operation rates and the existence of technologies:

$$
\boldsymbol{o}^{lc,et,t} \leq \sum_{s} \boldsymbol{\sigma}^{lc,et,s} \quad \forall\, lc \in LC, et \in ET, t \in T \tag{3.54}
$$

$$
\sum_{s} \boldsymbol{\xi}^{lc,et,s} \leq \sum_{t} \boldsymbol{\xi}^{lc,et,t} \quad \forall\, lc \in LC, et \in ET \tag{3.55}
$$

where the additional index s denotes the segments of the linearized investment cost curve (see e.g. Yokoyama et al., (2002); Weber and Shah, (2011); Voll, (2014) for more detailed descriptions). Finally, the following equations serve to determine the single, active segment of the cost curve corresponding to the chosen unit size.

$$
\boldsymbol{\xi}^{lc,et,s} \cdot \sigma_{\min}^{et,s} \leq \boldsymbol{\sigma}^{lc,et,s} \leq \boldsymbol{\xi}^{lc,et,s} \cdot \sigma_{\max}^{et,s} \qquad \forall\, lc \in LC, et \in ET, s \in S \tag{3.56}
$$

$$
\sum_{s} \boldsymbol{\xi}^{lc,et,s} \leq 1 \qquad \forall\, lc \in LC, et \in ET \tag{3.57}
$$

Investment costs $\boldsymbol{C}_{\mathbf{inv}}$ and operation costs $\boldsymbol{C}_{\mathbf{op}}$ are then calculated as:

$$\boldsymbol{C}_{\mathbf{inv}}^{cb,lc,et} = \sum_{s} \left(\boldsymbol{\xi}^{lc,et,s} \cdot c_{\text{inv,cst}}^{cb,et,s} + \boldsymbol{\sigma}^{lc,et,s} \cdot c_{\text{inv,lin}}^{cb,et,s} \right) \qquad \forall\, cb \in CB, lc \in LC, et \in ET \tag{3.58}$$

$$\boldsymbol{C}_{\mathbf{op}}^{cb,lc,et} = \sum_{t} \boldsymbol{o}^{lc,et,t} \cdot c_{\text{op,lin}}^{cb,et} \cdot \delta^{t} \qquad \forall\, cb \in CB, lc \in LC, et \in ET \tag{3.59}$$

where the operation costs are dependent on each time step of duration δ. $c_{\text{inv,cst}}$ and $c_{\text{inv,lin}}$ denote the constant and the linear part of each segment of the linearized investment cost curve. The operation cost factor $c_{\text{op,lin}}$ depends on the operation rate of the technology.

In order to compare the different cost, the investment costs are annualized using an annuity factor af

$$af^{cb,et} = \frac{i^{cb} \cdot \left(i^{cb} + 1\right)^{\wedge} lt^{et}}{\left(i^{cb} + 1\right)^{\wedge} lt^{et} - 1} \qquad \forall\, cb \in CB, et \in ET \tag{3.60}$$

which depends on the actor-specific interest rate i and the equipment-specific lifetime lt.

Costs and cost factors are further indexed over a set of cost balances CB to account for costs occuring to different actors. Thus operation costs can be linked to a cost flow into one balance (e.g. the building's tenants) and a cost flow out (i.e. revenues) of a another balance (e.g. the energy supplier).

PV

The PV model presented in section 3.3.2 estimates the solar potential based on height differences with surrounding buildings. As these heights are resulting from decision variables, an additional sizing of the panels in terms of area would lead to a non-linear problem formulation. Thus the assumption is made that if panels are installed, they always cover the entire part of the roof top area that is deemed as suited for PV electricity production. The implication for the cost calculation of panels is that there is no linear cost factor in (3.58).

3.5.3 Energy networks

The investment costs for energy networks are calculated based on the overall network length from (3.46) and an average pipe diameter dm_{ntw} for the case of the heating network (Girardin, 2012; Henchoz, 2016):

$$\boldsymbol{C}_{\mathbf{inv,ntw}} = (c_{\text{inv,l,dm}} \cdot dm_{\text{ntw}} + c_{\text{inv,l}}) \cdot \boldsymbol{l}_{\mathbf{ntw}} \tag{3.61}$$

3

Chapter 4

Regression model

Highlights

- Multiple linear regression model for the estimation of the annual heat demand of several building types
- Consideration of parameters characterizing the buildings and their surroundings

The content of this chapter was originally published in (Schüler et al., 2015).

Section 1.1.3 listed the unknowability of the present state as one consequence of complexity, It was further stated that one part of this unknowability can be classified as epistemic, or reducible, uncertainty. Possibilities for this reduction are the acquisition of more data, the refinement of models, or the employment of sub-models (Kiureghian and Ditlevsen, 2009, p. 107). Sub-models can be employed to derive the values for a variable of interest from more basic variables, for which values might be available. The concrete use case for this work is the estimation of annual heating demands of buildings. This information is required to address questions concerning the further development of an existing neighborhood. However, measured demands are only available for a part of the building stock (section 6.2).

Suited computational methods for this purpose are statistical and simulation modeling (Swan and Ugursal, 2009). Due to their mathematical nature, both modeling methods have different strengths and weaknesses regarding the representation of the different aspects of buildings (Foucquier et al., 2013). While the representation of statistic or stochastic information as user-related aspects is an issue for physical models, the representation of physical aspects as building geometry or topography is usually less or not considered by stochastic models. Due to their general higher flexibility in incorporated information (Mastrucci et al., 2014; Guerra Santin et al., 2009), a stochastic method in the form of multiple linear regression modeling is developed for this work. In order to overcome the previously mentioned drawbacks of statistical models and better represent physical aspects, a set of geometric parameters is included in the regression. An aspect so far neglected by regression models of buildings' heat demand is the influence of solar gains and microclimate. This aspect is substantially characterized by the surrounding topography (Robinson et al., 2011, p. 116). Thus meaningful parameters are included, which are suited to represent urban topography and are easily derivable from the available data.

A reliable estimation of the heat demand of existing buildings is required to improve the reliability of decisions concerning the design and operation of energy systems and refurbishment measures. An estimation on such a scale in turn requires to regard several building types representing as comprehensively as possible the entire building stock. Such an estimation further requires a holistic representation of aspects influencing the heat demand of buildings, namely their geometry, fabric, users and surrounding environment (figure 4.1). The representation of these different aspects needs building specific information. However, the availability of information in terms of both different parameters and a complete parameter set for each building usually limits the detail of the representation and the number of buildings, respectively, for which a heat demand estimation can be made. Thus the elaboration of the regression model starts with an assessment of the data availability.

4.1 Data description

The study is carried out on basis of georeferenced data for the canton of Geneva in Switzerland. Thus next to mostly urban areas also rural areas are considered. The data are obtained from the territorial information system for Geneva (SITG) (SITG, 1957), which provides a large amount of publicly available data for the entire building stock. The 115 listed building types are sorted into 7 categories according to expectable similarities in heat demand: residential buildings, offices, commercial buildings for wholesale and retail, industries (factories and workshops, excluding storehouses), educational buildings (schools, universities and research institutes), healthcare buildings (excluding sport facilities) and hotels (including guest houses). An eighth building type represents less frequent buildings with yet a considerable heat demand (e.g. museums, libraries, churches, stations, airport). Further buildings with minor or without heat demand as e.g. garages are excluded. Figure 4.2 shows the resulting number of buildings per building type, the number of buildings for which annual heat demand measurements are available and the number of buildings regarded in the regression analysis excluding records with incomplete parameter sets.

Figure 4.3 summarizes all used parameters and their availability for the regarded building stock. The annual heat demand of each building is available in the form of an average heat

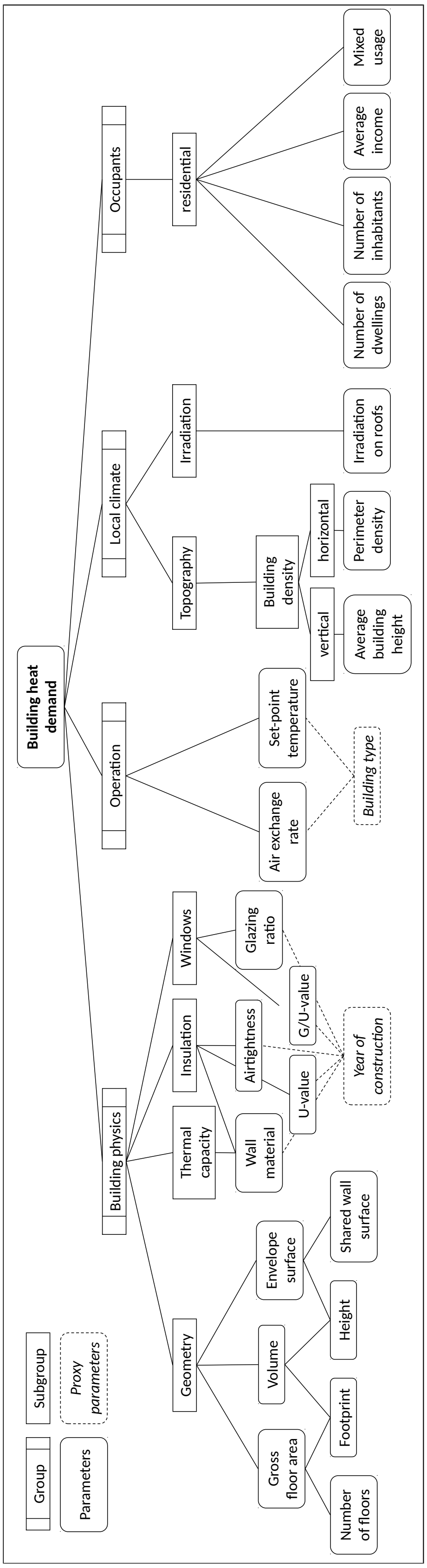


Figure 4.1 – Parameters influencing the heat demand of buildings, grouped thematically

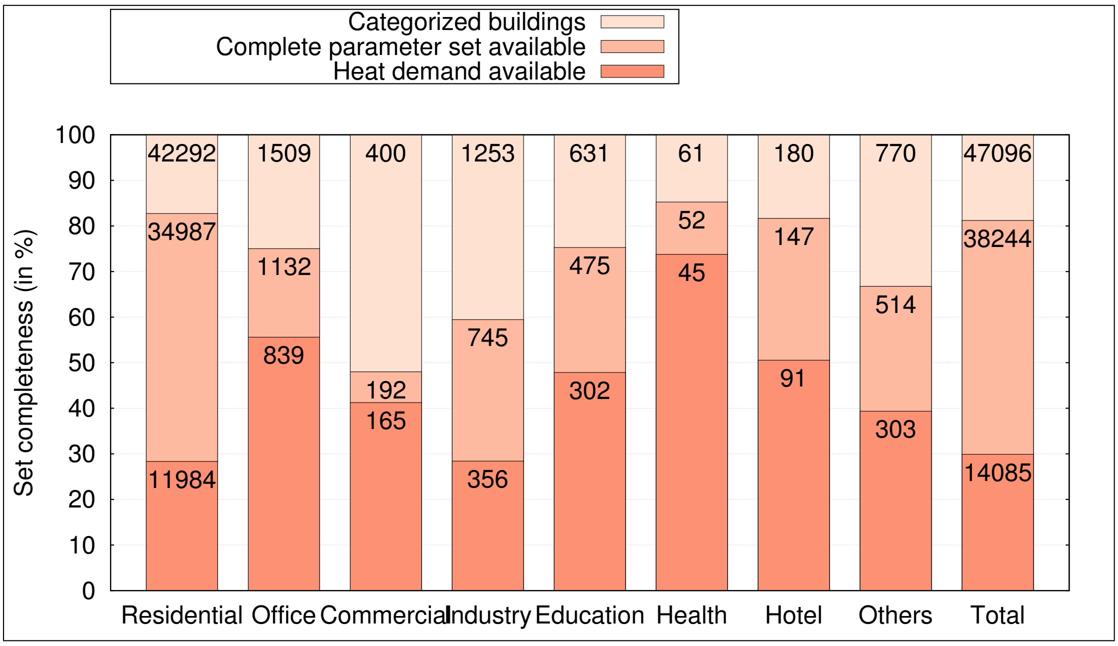


Figure 4.2 – Number of buildings and according data availability per building type (absolute values indicated)

demand for the years 2010 to 2012, which includes both hot water and weather-corrected space heating energy demand, normalized by the energetic reference floor area (SRE) of the building. However, it is refrained from using the normalized values for two reasons: first, the SRE is almost only available for buildings for which heat demand data are available. Predicting the SRE specific demand would thus not help to predict the total demand for the rest of the building stock. Second, regressing the normalized value does not allow to compare the influence of the floor area against other parameters. Therefore the total demand is obtained by multiplying the area specific heat demand and the energetic reference floor area (SRE) of each building.

Information about the geometry of buildings are available from both an extensive building cadaster and a three-dimensional city model. The cadaster includes height and number of floors. The gross floor area is estimated by multiplying the number of floors with the footprint area. Analogously buildings' volumes are computed using their footprint areas and height. The three-dimensional model provides further information about the buildings' envelope in terms of total, shared and unshared wall surfaces as well as roof surface and average roof pitch. An important further aspect is the buildings' fabric. Since information about e.g. U-values and airtightness is not available, the building's construction period is used as a representing parameter (figure 4.1) (Swan and Ugursal, 2008). Reliable information about renovations of buildings is not available and thus left out of the analysis since neither is the type of renovation specified nor is a clear distinction possible if a building is not renovated or the entry is missing.

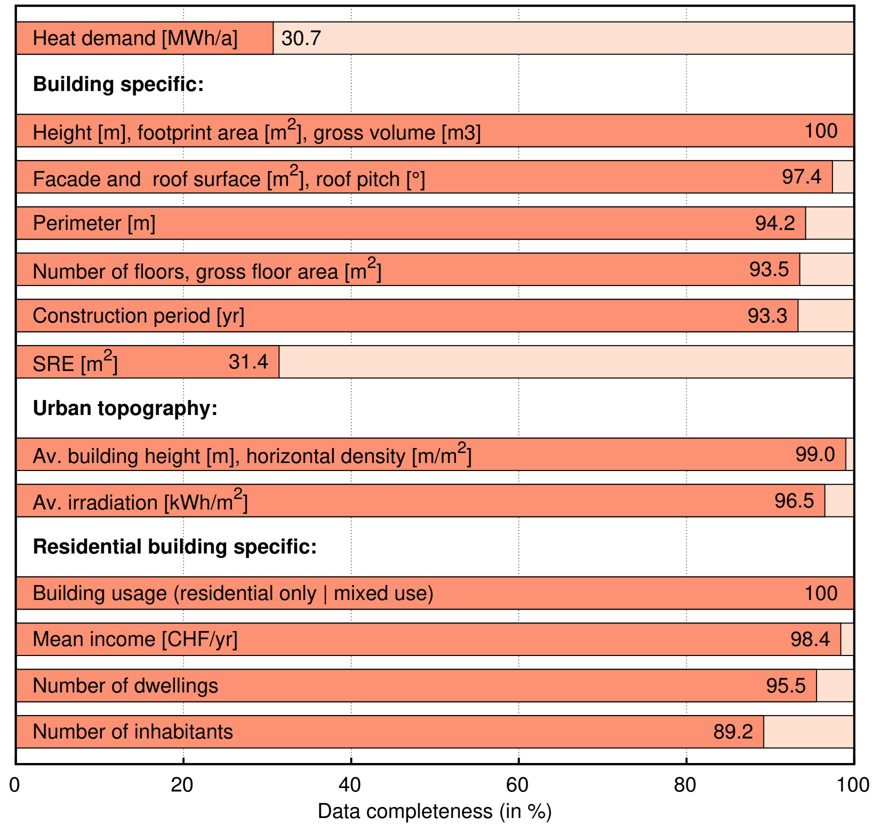


Figure 4.3 – Parameter availability and completeness for the total 47096 categorized buildings and 42292 residential buildings (percentage values indicated)

To reflect potential effects of the urban topography on the heat demand, two additional parameters are defined. As a basis for their definition, the partition of the canton of Geneva into 474 statistical sectors, is used. Two considerations led to their definition: (i) Long and shortwave radiation processes and micro climate are rather influenced by the external dimensions of buildings than by their area or volume. (ii) Horizontal and vertical topography might have different effects on the demand since they are influencing obstruction to solar irradiation and convective heat transfer in different ways (Robinson et al., 2011). Thus the vertical topography is represented by the average building height within each of the statistical sectors. The horizontal topography is represented by the ratio of the sum of all buildings' perimeters pm_{blg} within one sector and the sector's area A_{sct}:

$$p_{\text{sct}} = \frac{\sum pm_{\text{blg}}}{A_{\text{sct}}} \tag{4.1}$$

These factors, specific to each sector, are attributed to the respective buildings and together indicate the amount of façade surfaces within each sector normalized by the sectors area. To further specifically represent the effect of solar gains, data of a solar cadaster is used, which gives for every roof surface the area specific, average annual irradiation.

Additional information is available for residential buildings in the form of number of dwellings per building, inhabitants per building and their approximate income. The latter is not available on building level but on the level of the previously mentioned statistical sectors as average income. Also information is available if a building is used only for residential purposes or for other purposes as well (mixed).

4.2 Regression analysis

The suitability of various regression methods for estimating the annual heat demand of buildings has been compared by different authors and it is mostly found that linear regression models have a performance comparable to others and thus are preferable since being computationally more efficient and easier interpretable (Kolter and Ferreira, 2011). Thus linear multiple regression models for heat demand prediction are developed separately for each building type using the statistical software R (R Core Team, 2013). The models are fitted using the Ordinary Least Squares method. The initial regression model for each building type included the full parameter set as listed in figure 4.3 except the SRE due to previously stated reasons (4.1). Kolter and Ferreira (Kolter and Ferreira, 2011) showed how a logarithmic transformation of predicted variable and predictors substantially improves the performance of methods for the regression of buildings' heat demand. Thus all parameters whose distributions are clearly skewed on the original scale, are logarithmically transformed. Construction periods and information about mixed usage are included as factorial variables.

The assumptions of multiple linear regression are carefully verified and the prediction error is estimated using the mean average percentage error (MAPE) and the root-mean-square error (RMSE) for both the logarithmically scaled model outputs (log) and the ones transformed back to the original scale. This makes it possible to compare the performance of the models of the different building types against each other and with values reported by other authors.

Due to the partly very large sample size, 10-fold cross-validation is chosen since being a non-exhaustive method. However, the inclusion of the building period as factorial variable causes issues when the entire sample per category contains only one building built within a specific period. Since every building will be once part of the test data, the model will then not be trained on data containing this specific period thus preventing the application of the resulting model for this building. The issue is circumvented by excluding the regarding buildings from the cross-validation. This is the case for the categories of commercial (1 building excluded), educational (1) and healthcare (3) buildings.

4.2.1 Models for the whole building stock

Figure 4.4 visualizes the quality of the annual heat demand prediction of the different models. Results of the regression analysis for the different building types are shown in table 4.1. The models are able to account for between 73.1% and 88.9% of the variances (R^2). The difference between R^2 and the adjusted coefficient of determination $\bar{R}^2$, naturally increases with decreasing sample size (Makridakis et al., 1997). Considering the sample size, the highest share of explained variance is achieved by the residential model with 88.9%.

4

Table 4.1 – Results of the regression analyses for the different building types

	unit	residential	office	commerce	industry	education	health	hotel	other
R^2		0.889	0.795	0.800	0.744	0.838	0.915	0.889	0.731
$\bar{R}^2$		0.889	0.789	0.760	0.725	0.824	0.854	0.861	0.712
MAPE	%	17.8	39.8	47.0	121.6	38.7	36.9	30.2	58.4
MAPE (cross-validated)	%	17.9	41.6	64.4	167.1	44.0	85.2	38.6	66.2
RMSE (log)		0.243	0.488	0.555	0.714	0.468	0.428	0.374	0.623
RMSE (log, cross-validated)		0.244	0.506	0.666	0.783	0.531	0.765	0.488	0.674
RMSE	MWh/a	61.3	423.4	458.1	361.5	419.6	460.0	432.1	271.3
RMSE (cross-validated)	MWh/a	61.6	449.1	674.5	380.2	691.3	1690.3	642.5	306.0

The p-values are for all models close to zero demonstrating that the models are globally significant and the null-hypothesis can be rejected. The scatterplots of the residuals against the predicted values are checked but reveal no pattern for any building type thus showing no heteroscedasticity in the errors.

The lowest errors are achieved for the residential building type with a MAPE of 17.8% and an RMSE of the logarithmically scaled outputs of 0.243. The MAPEs for hotel, healthcare, educational and office buildings range between 30.2% and 39.8%. Three

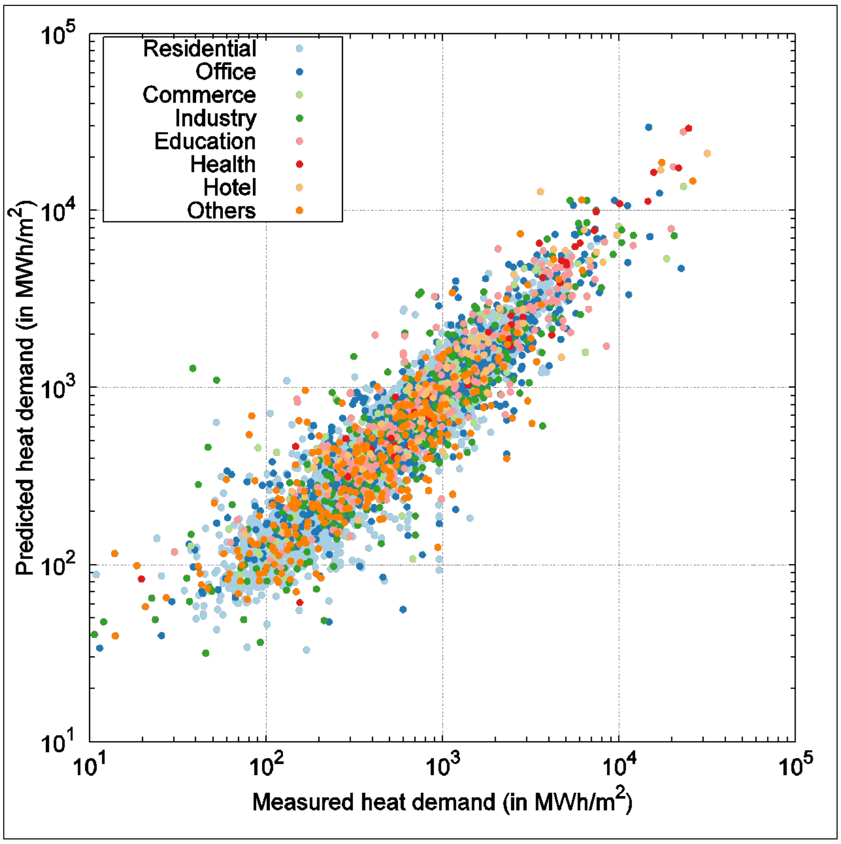


Figure 4.4 – Relation between predicted and measured heat demand of the developed regression models per building category

4

aspects of industrial buildings differ quite considerably from building to building which might explain the very high error for this type (MAPE: 167.1%): (i) The share of gross floor which is heated, (ii) the building's operation with set-point temperatures and air exchange rates and (iii) the internal heat gains or loads due to installed equipment and people. These arguments might as well apply to commercial buildings (MAPE: 47.0%) although the expectable differences should be lower. Thus a common conclusion for these both categories is that a consideration of the specific type of industry or commerce might reduce the model error. The high model error for the last building type representing other buildings (MAPE: 58.4%) is not surprising because of the diversity of expectable demand patterns within this type.

The discrepancy between RMSE of scaled (log) and unscaled (MWh/a) model output stems from the differing average heat demand of the buildings. For example a high RMSE for unscaled outputs of hotel buildings is not a contradiction to a low RMSE for scaled outputs and a low MAPE since the hotel buildings are found to have the highest average heat demand within the measured demand data.

The difference between the errors for models of the entire data sets and the cross-validated errors, i.e. the optimism index, is lowest for the residential building model (ΔMAPE: 0.1%) and considerably low (ΔMAPE: 1.6 to 8.4%) for all other categories apart from industrial and healthcare buildings. The high index for the healthcare building model (ΔMAPE: 48.3 %) hints towards an overfitting of the data due to a small sample size of 42 buildings. For industrial buildings (ΔMAPE: 45.5 %) overfitting is not so likely to be a problem since the sample size of 281 buildings is quite large. It rather points out again the low suitability of statistical models for predicting industrial heat demand without having further information about the type of the industry.

The good model results for residential buildings hint towards a suitability of the chosen parameter set for this category. A further inclusion of building type specific parameters is expected to improve the models for other categories.

4.2.2 Model for residential buildings

The influence and significance of the various parameters is assessed more in detail exemplary for the model of residential buildings since it represents the biggest part of the building stock. Table 4.2 lists the estimated model coefficients, their standard errors, t-values, significances and variance inflation factors. When interpreting the values it has to be noted that the logarithmic transformation of some of the parameters prohibits a direct comparison in terms of value to unscaled parameters.

The interpretation of the regression coefficients requires further the prevention of multi-collinearity (Makridakis et al., 1997). Thus only a limited set of all available geometric parameters is included. Multi-collinearity is assessed by examining the variance inflation factors (VIF). The parameters are selected thus that the VIFs showed values at maximum around 10 indicating no serious multi-collinearity issues (Hair, 2006). Of all initially used parameters only the number of floors is excluded from the model for residential buildings due to the results of a stepwise regression.

Table 4.2 – Statistical summary of the linear regression model for residential buildings: factorial coefficients are compared against a reference value which is thus not listed. The reference values are "<1919" for the building period and "Mixed usage" for the usage of residential buildings. Coefficients marked with lt are logarithmically transformed prior to the regression.

Parameter	Est. coeff. ($\cdot 10^{-3}$)	Std. Error ($\cdot 10^{-3}$)	t-value	Signif.	VIF
Intercept	6846.46	48.26	141.85	<0.0001	
Building specific					
Height	22.81	0.66	34.46	<0.0001	5.03
Gross floor area^{lt}	244.61	9.63	25.41	<0.0001	11.04
Shared façade surface^{lt}	-3.22	1.40	-2.30	0.0215	1.34
Roof surface^{lt}	429.54	11.13	38.58	<0.0001	4.12
Roof pitch	-4.07	0.24	-16.90	<0.0001	1.83
1919-1945	17.63	9.45	1.87	0.0621	1.49
1946-1960	-7.62	8.83	-0.86	0.3881	1.82
1961-1970	-0.22	9.12	-0.02	0.9808	2.05
1971-1980	-7.28	9.29	-0.78	0.4332	1.89
1981-1985	-6.67	14.01	-0.48	0.6340	1.24
1986-1990	-43.51	12.00	-3.63	0.0003	1.36
1991-1995	-89.11	11.26	-7.91	<0.0001	1.53
1996-2000	-99.23	11.10	-8.94	<0.0001	1.58
2000-2005	-183.00	13.00	-14.08	<0.0001	1.62
2006-2010	-382.15	20.23	-18.89	<0.0001	1.21
Urban topography					
Average building height	0.18	0.64	0.28	0.7807	2.68
Horizontal density	875.77	116.56	7.51	<0.0001	1.99
Average irradiation	0.15	0.02	6.89	<0.0001	1.37
Residential building specific					
Number of dwellings^{lt}	161.31	6.81	23.70	<0.0001	6.64
Number of inhabitants^{lt}	65.38	5.95	10.99	<0.0001	5.11
Average income	-0.00	0.00	-4.66	<0.0001	1.78
Residential only	-35.17	5.61	-6.27	<0.0001	1.35

Almost all chosen parameters are highly significant for the model of residential buildings. The estimated coefficients for geometric parameters reveal the importance of these parameters for the estimation of buildings' heat demand. Both an increasing heat demand with building dimensions and a decreasing demand with increasing area of shared walls is reasonable. The estimated coefficients for construction periods show that the demand of buildings constructed from 1919 on generally increases with building age. Since buildings constructed before 1919 are forming the reference period, the model further shows that those buildings tend to have a lower heat demand than buildings constructed between 1919 and 1945 and buildings constructed only after 1985 tend to have a considerable lower heat demand. This result is highly in-line with the findings of Aksoezen et al., (2015) and reveals a non-linear dependency of heat demand on building age. Thus this effect would be missed by purely linear models e.g. by considering the age as an integer in a linear regression model. The decrease in heat demand of buildings constructed after 2005 is further remarkable.

The horizontal density factor is found to have a high estimated coefficient. An interpretation of the topographic factors, however, is complicated since the building density affects heat demand in different ways. Due to increased obstruction denser districts should correspond to lower solar gains and thus increased heating demand. At the same time the increased amount of façade surfaces means also an increased long-wave exchange and thus a decreased heating demand. When assessing the significance of the chosen topographic factors, it has to be taken into account, that both factors are not defined per building and thus rough in comparison to most other parameters.

The data from the solar irradiation cadaster did not have a considerable effect. Here again the question is if the effect of solar gains on annual heat demand on a regional scale is generally not so high, which is e.g. quite plausible for older buildings, or if more suited parameters could be identified for a better representation of this effect. In fact the solar irradiation cadaster represents only the amount of incident irradiation on roofs. The effect of solar irradiation on vertical walls is thus not specifically represented. However, the previously discussed topographic parameters represent the amount of façade surfaces within a sector normalized by sector area and should thus incorporate information about the amount of shaded surfaces. Furthermore information about glazing ratios of buildings should be of particular importance for the estimation of the effect of solar gains.

The analysis of the additional parameters for residential buildings reveals that the number of dwellings per building has a remarkable bigger effect on heat demand than the number of inhabitants. The information about average income has almost no effect, which might again be due to the fact that this information is only available at the level of statistical sectors. The negative estimated coefficient for the information that a building is only used for residential purposes means that these buildings generally have a lower heat demand than buildings with mixed usage.

4

Chapter 5

Data model

Highlights

- Developement of a data model for interactive optimization
- Presentation of the extension of an existing semantic 3D city data standard (CityGML) that allows to efficiently store many alternative scenarios of a city
- Definition of the interface between the data model for interactive optimization and the city data standard

The content of this chapter was first published in (Schüler et al., 2018a).

5

The developed planning support sytem URB^{io} has several requirements in terms of data handling and storage: first of all, the generation of a multitude of scenarios means that many instances of a city with all its relevant entities and their characteristics need to be treated. Moreover, an exhaustive search within the large decision space implies that almost every characteristic of those entities might change. Due to the context, city-related information has to be handled which implies georeferenced information. Ideally this information can be displayed in maps easily and with a great flexibility in amount and detail. Furthermore, the adoption of an existing data standard would facilitate the applicability of URB^{io} to different planning projects and cities. Finally, the data model should allow several users to collaborate on the same project to enable participative planning. These requirements can in principle be assigned to either the *methodology* of interactive optimization or the *context* of urban planning.

The methodology of interactive optimization requires a data model that allows to depict the changes made by a user which can be transformed into input information to the algorithms. The calculated results have to be stored again in order to be visualized in the interface.

The context of urban planning requires a sufficiently detailed urban model. Such a model needs to contain all representative entities implied in a planning process together with their spatial and non-spatial characteristics and their mutual relations and dependencies. However, collecting, harmonising and integrating huge quantities of urban data for such a model can be a tedious and resource-intensive task. This has led to the establishment of open, and extensively documented standards like CityGML[1] (Gröger et al., 2012). As a consequence, the availability of semantic 3D city models has increased in the last years (CityGML, 2018a). This is again a good argument for adopting the CityGML standard, as it facilitates the application of URB^{io} to different planning projects and cities. A further advantage of CityGML is the existence of a number of tools which cover most of related needs in terms of ETL (Extract, Transform, Load) operations, database implementations for data management like the open-source 3D City Database[2] (Kolbe et al., 2016)), web-based solution for data access (Web Feature Services), and visualisation solutions like Google Earth or Cesium WebGlobe (Yao et al., 2018). In particular, the possibility to access and explore urban data by means of maps allows to better understand the results, and consequently to define further tasks and analyses. An extensive search of the decision space, which is a key strength of the interactive optimization approach, implies that it is required not only to store one instance of the city but a large number of alternative scenarios, which need to be managed.

Initial work on extending CityGML to support multiple versions of a city model has been carried out by Chaturvedi et al., (2017). Their focus is on adding support for the management of versions and history within semantic 3D city models in version 3.0 of CityGML, which is expected for 2019 (CityGML, 2018b). However, the proposed approach is not meant to be backported to the current version 2.0, as it changes rather deeply the overall data model.

The path followed here is partially inspired by the work of Sindram and Kolbe, (2014), who propose a systematic approach for modelling urban planning actions by means of complex transactions on semantic 3D city models. It aims to be compatible with the current version of CityGML by the definition of a new ADE. The mechanism of Application Domain Extensions (ADE) (van den Brink et al., 2013) allows to extend CityGML by defining entities and properties additional to the current ones. Alternatively new feature classes or city objects can be specified by derivation from the general GML class _Feature, the _CityObject base class, or any specific CityGML class.

Consequently, this chapter explains the work carried out in order to link the interactive optimization framework for urban planning URB^{io} with CityGML using the newly developed Scenario ADE, which was described first in (Schüler et al., 2018a). In order to achieve this, the two following contributions are proposed as a response to the identified gaps:

[1] www.citygml.org
[2] www.3dcitydb.org

1. the extension of CityGML in order to cope with scenarios (section 5.1)
2. the definition of a dedicated data model for interactive optimization (section 5.2)

5.1 The Scenario ADE of the CityGML standard

The development of the Scenario ADE of the CityGML standard is the work of Agugiaro, (2017). Consequently, the purpose of this section is to rather provide an overview of the Scenario ADE and to explain how it is employed within the developed PSS URB^{io} . Therefore, the UML diagram depicted in figure 5.1 illustrates the Scenario ADE elements and their connection to the core CityGML classes.

As mentioned initially, many possible instances of the considered part of the city have to be handled and stored. To do so effectively, however, it is preferable to avoid storing all features and attributes for every change. Consequently, the Scenario ADE is designed to store only incremental changes to a base city model. For this purpose the concept of a scenario is introduced.

5.1.1 Scenarios

A scenario can be regarded as a container for changes. Each scenario can have a name, description, and information about its creation and temporal validity. It can be linked to any city object. Since in CityGML a city object can also be a group of city objects, a scenario can be linked to a number of buildings or parcels, e.g. the ones considered for the current planning project. Any city object can belong to one or many city models. Thus, by defining city models and linking them to scenarios, objects common to several scenarios need to be stored only once, even if some of their attributes may change (see section 5.1.3). In this way it is sufficient to store for each scenario to which city model its changes are refering to. Furthermore, if a scenario does not comprise any changes of city objects, no city model needs to be stored, as indicated by parentheses in figure 5.3.

A scenario can inherit from another scenario. Thus changes made within preceeding scenarios can be traced back and aggregated if required (see figure 5.3). The changes associated to a scenario can be of different types, which are described in the following subsections.

5.1.2 Scenario parameters

Scenario parameters can generally be used to store information that does not correspond to any attribute defined by the CityGML standard. Especially aggregated, i.e. district or city-wide, information like densities or share of renewable energy sources are not defined by the standard. The reason is that when simply retrieving this information, it can

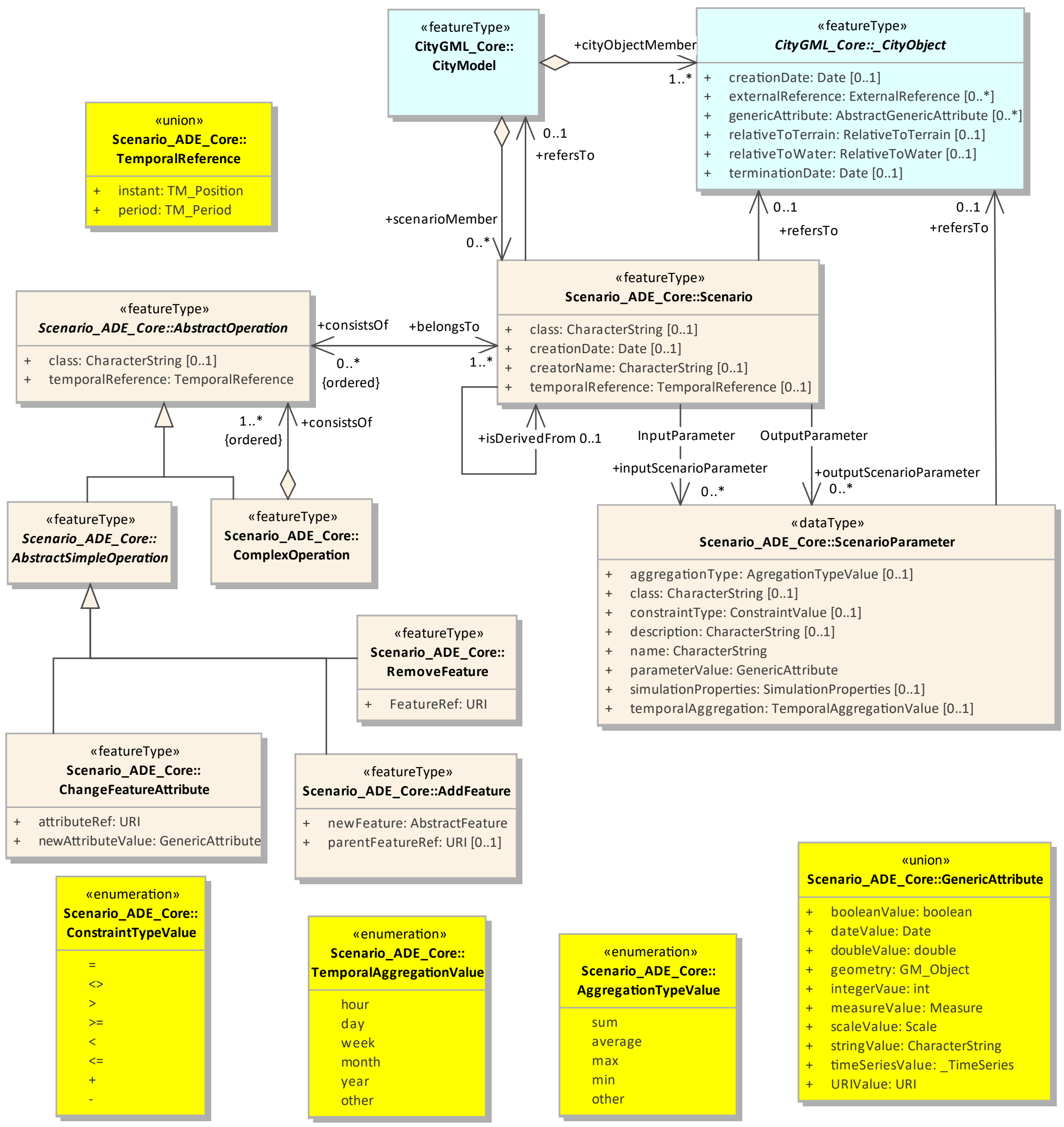


Figure 5.1 – Excerpt of the UML diagram of the Scenario ADE, core module (Schüler et al., 2018a)

be calculated on demand by aggregating the stored, finer grained information for all buildings or energy conversion systems, like number of floors, footprint, or energy supply from energy conversion systems using renewable sources. However, when this information is for example a required input to a calculation (i.e. simulation or optimization), e.g. by defining a constraint on the building density, a numeric value has to be stored for this specific parameter (see section 5.2.3). The considered criterion is denoted by `name` while its value is denoted by the attribute `parameterValue`. The scenario parameters are further differed into input and output parameters to or from a calculation. When a criterion is an objective, the attribute `constraintType` can be used to indicate if this parameter shall be maximized (+) or minimized (-). Otherwise it is used to fix parameters at certain values (=) or to specify upper (≤,<) or lower bounds (≥,>).

5.1.3 Operations

Changes of features that are defined by the CityGML data model or any of its ADE are supposed to be stored via operations. Operations are differentiated into those which add a feature, remove a feature, or change the value of a feature's attribute. A scenario can have zero to many operations and also operations themselves can be assigned to several scenarios. This avoids the need to store identical operations, thus reducing redundancy and storage size.

5.1.4 Time series

Both scenario parameters and operations can be associated to time series and thus represent temporally varying values. Note that only complete time series can be changed and not single values of them. For further details of the time series module it is referred to the Scenario ADE documentation (Agugiaro, 2017) or the Energy ADE documentation (Agugiaro and Holcik, 2017), respectively.

5.2 Data model for interactive optimization

The interactive optimization workflow within URB^{io} using Mixed Integer Linear Programming and parallel coordinates is described in (Cajot et al., 2017; Cajot et al., 2018). The focus here is to describe the workflow from a data perspective along with the corresponding data model (figure 5.2).

5.2.1 Projects & users

A project in URB^{io} is owned by one or more users to allow them to collaborate on it. It is created by choosing a name (`project_name`) for the project and a city where the

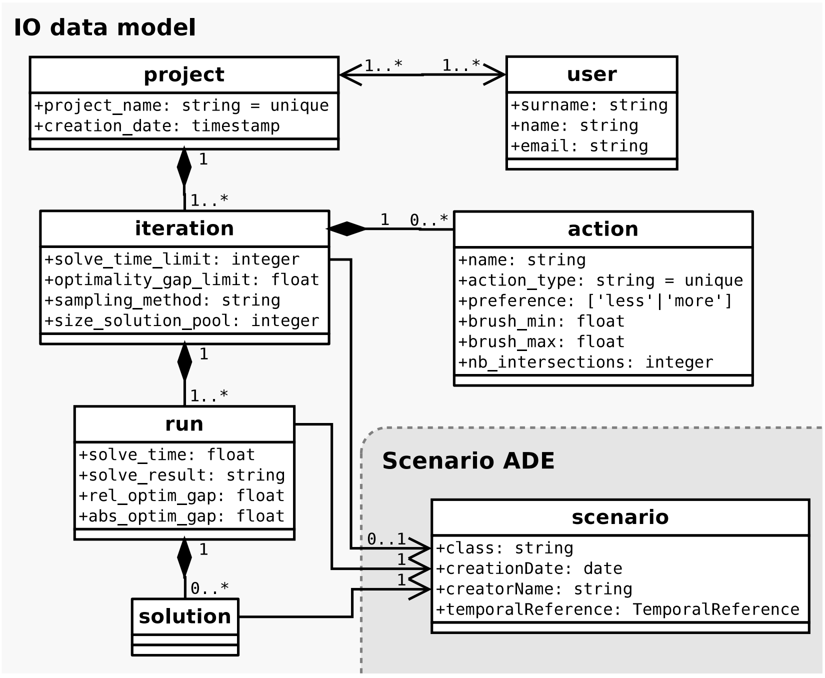


Figure 5.2 – UML diagram of the data model for interactive optimization and its relation to the CityGML Scenario ADE

planning project is situated. Afterwards an initial spatial project perimeter can be chosen from the map, comprising the districts, parcels, or buildings of interest. This perimeter, however, can be still updated later in the workflow depending on the project's needs. Being interactive, this workflow is an alternation between changes made by the user and changes resulting from computer calculations (figure 5.3). It starts from a base scenario, which comprises initial information about city objects of the planning project at hand, like parcels on which to build or already existing buildings, and information considered immutable, as e.g. meteorologic conditions. From there the workflow proceeds iteratively.

5.2.2 Iterations & actions

Each iteration starts with changes made by the user. These changes can concern information of three types:

- The information can be specific to the methodology. This information is stored as attributes of the **iteration** class. It concerns the chosen sampling method, like systematic sampling (Thompson, 2012) or quasi-random sampling with e.g. Sobol sequences (Burhenne et al., 2011), to explore the decision space for criteria which shall be varied (`sampling_method`). Furthermore, optimization-specific settings can be stored such as an optimality gap (`optimality_gap`), which specifies e.g. the maximum expectable difference between a solution and the global optimum

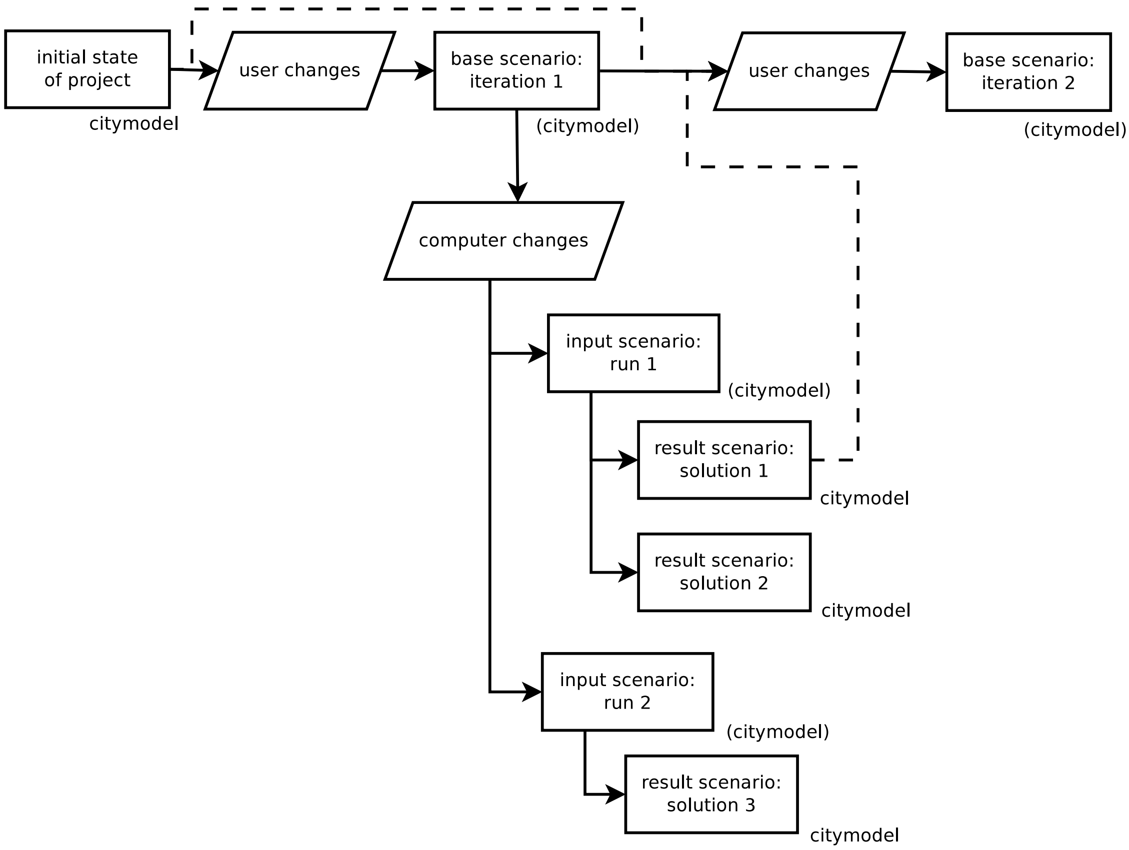


Figure 5.3 – Flowchart of the interactive optimization workflow (dashed lines indicate alternative paths of the workflow)

(Lawler and Wood, 1966), and a time limit (solve_time_limit), which cause the optimization to stop once either stopping criterion is met, and the number of solutions to return per optimization run (size_solution_pool). While, in principle, these changes could also be made using the parallel coordinate interface, they are more commonly made using forms, buttons, and dropdown menus.

- The changed information can be context-specific information which is not geo-referenced. These changes are mainly made using the parallel coordinate interface by selecting and brushing the displayed axes (name) in order to define actions of different types (action_type) to be carried out on the associated criterion: (i) If the action is to optimize a criterion, it can be either maximized or minimized depending on the selected preference. (ii) If the action is to constrain a criterion, it is assured to stay above or below certain limits (brush_min / brush_max, preference). (iii) If the action is to explore the range of a criterion, it will be varied systematically within this range (brush_min, brush_max, preference) according to the number of desired axis intersections (nb_intersection) if the sampling method requires so. The actions on the different axes are instances of the **action** class.

- Finally, the changed information can be context-specific information which is geo-referenced e.g. the number of floors of an already existing building or the permission to build ground source heat pumps on a specific parcel. These changes are stored using the operation mechanism of the Scenario ADE (see section 5.1.3).

5.2.3 Runs

Depending on the chosen sampling algorithm and optionally how many intersections per axis (nb_intersections) were requested by the user, the algorithm generates input scenarios for optimization runs by translating the axes actions into values for the parametrized constraints or objective weights, respectively. These values are stored as scenario parameters (see section 5.1.2). An optimization run is further characterized by optimization-specific information, namely the actual time needed to finish (solve_time), its result status (solve_result e.g. solved), and the optimality gap in relative and absolute terms of its final solution (rel_optim_gap, abs_optim_gap).

5.2.4 Solutions

Depending on the user settings, each optimization run can generate zero, one or many solutions: (i) If no solution is generated this means that no feasible configuration respecting all constraints could be found, at least not before reaching the solve time limit. (ii) A single stored solution is always the best performing configuration found within the time limit or the optimality gap. (iii) If a pool of solutions is requested from an optimization run (size_solution_pool), several solutions are stored. In contrary to solutions from different runs, these solutions are required to all respect the same, run-specific constraints. However, they differ in the choices for decision variables, thus still resulting in different plans. Consequently all but one of the solutions are sub-optimal. For every solution a result scenario (see section 5.1.1) is stored along with its associated operations and scenario parameters.

5.2.5 Continuation of workflow

An iteration stops once either all requested runs are finished or the user interrupts the generation of new runs. Since every solution is loaded into the interface as soon as it is available, the user can already start to explore the solutions found so far while still new solutions are created. Based on the gained insights, and if the results are not yet satisfying, the user can initiate a new iteration by deciding to (i) proceed from any of the found result scenarios, adopting the intermediate changes on input parameters or city object attributes or (ii) proceed from the base scenario of the current iteration or even (iii) revert previously made changes to proceed from an earlier state of the planning project, be it a base or a result scenario. The workflow continues with the steps described in section 5.2.2.

5.3 Link between the data model for interactive optimization and the Scenario ADE

The link between the data model for interactive optimization and the CityGML Scenario ADE consists in the creation of scenarios for instances of one of the three classes **iteration**, **run** or **solution** (section 5.2). The relations between those scenarios and these interactive optimization class instances are realized using an associative table. The actions, as explained in section 5.2.2, are translated internally into input information for the optimization. These are assigned to a run scenario and stored as parameters of `type` "input" using the scenario parameter mechanism of the Scenario ADE (see section 5.1). The `class` attribute is used to further differentiate between objectives and constraints (figure 5.2). For parameters of type *objective*, the parameter value can e.g. indicate a weight for the weighted sum method for multi-objective optimization (Marler and Arora, 2010). The attribute `constraintType` is used to indicate if this parameter shall be maximized (+) or minimized (-). Those attributes are used likewise for constraints, in order to fix parameters at certain values (=) or to specify upper ($\leq$,$<$) or lower bounds ($\geq$,$>$).

Optimization results are mainly stored in form of scenario operations, which are assigned to an according solution scenario. Only information that can not be retrieved by aggregating the stored, finer grained information of e.g. all buildings of a scenario, is stored explicitly as scenario parameters of type "output".

Finally the inheritance mechanism between scenarios is employed to allow for the different options listed in section 5.2.5.

Chapter 6

Case studies

Highlights

Description and data of three case studies differing in their ...

Planning scope	new development, redevelopment, and development of an existing district
Geographic location	Geneva and Singapore

The contents of sections 6.1 and 6.4 were first published in (Schüler et al., 2018b), while the contents of section 6.3 appeared in (Hsieh et al., 2017). Material presented in section 6.2 is to be published in (Schüler and Cajot, 2018b).

6

In the previous chapters the employed computational methods and developed models were presented that allow to address the fact that urban systems comprise various phases, actors, domains, and scales. This required, moreover, to adopt and develop computational strategies in order to deal with the epistemic uncertainty of those systems and the large amount of inherent information that needs to be handled and stored.

These computational methods together with decision support and interactive optimization methods and features developed by Cajot, (2018) form the planning support system URB^{io} . In the following, its suitability to address the aspects of urban complexity as presented in section 1.2, is demonstrated. This means in particular to show the impact of decisions typically taken during different phases of an urban development and to identify future states that are optimal with respect to the combination of certain objectives.

In order to demonstrate its applicability to different contexts and ranges the developed planning support system is applied to three different case studies. These case studies are presented in this chapter. In the presentation of the case studies the focus is put on the aspects required to build and run the models. For background on the planning aspects and documents for the Geneva case studies, it is referred to Cajot, (2018).

6.1 Greenfield planning project in Switzerland: "Les Cherpines"

The case study, based on which the model was initially developed, is an ongoing greenfield development project aiming at transforming a rural zone into a neighborhood named "Les Cherpines". This zone is located in the south-eastern part of the canton of Geneva, Switzerland, about 5 km away from the city center. The climate of Geneva is temperate with cool winters and warm summers. The development area comprises 58 ha and shall host about 3000 dwellings and 2500 jobs by 2030. It is assumed for this work that 67.5 % of the gross floor area is used for residential, 30 % for office, and 2.5 % for commercial purposes. A neighborhood master plan was issued in 2013 and defines several goals for the new development (Office de l'urbanisme, 2013). To cope with the increasing demand for residential and office space in the canton (Office de l'urbanisme, 2011), it shall achieve a high FAR. Parcels that are located close to the major street bordering the neighborhood on its south-eastern side, shall be preferably used for commercial and office purposes to increase their visibility.

The new development shall meet "eco-district" standards by covering at least 75 % of the energy demand from renewable sources and constructing buildings according to the requirements of the Swiss energy standard MINERGIE-P for thermal insulation. An industrial zone is located towards the southeast of the area with already installed pipes for a heating network. Consequently an attractive option could be to employ the incidental waste heat for satisfying the new neighborhood's energy demands. The waste heat is taken as being constantly available over the year with a power of 10.75 MW at a temperature of 20 °C. Further envisaged energy sources are geothermal heat and electricity from PV. As the new development is located within the city boundaries, some infrastructure is already existing, e.g. electric lines are passing by all blocks. Consequently no installation costs for an electric grid are considered.

The spatial allocation of buildings is performed based on a preliminary site layout which is defined by the master plan (Office de l'urbanisme, 2013). It indicates the foreseen locations of major streets and some specific functionalities as an industrial zone in the southwestern part and a sports ground in the northern part of the area. In order to limit the initial scope of this study, the aforementioned elements were taken as fixed so that the remaining elements (i.e. buildings for residential and commercial purposes and for offices) are to be determined by the optimization. Based on the layout of the master plan, a map is generated (see figure 6.1) showing the various elements considered by the optimization model.

Figure 6.1 – Map of the case study "Les Cherpines"

The areas between the streets, which are already sketched in the preliminary layout (figure 6.1), are defined as blocks and all blocks not containing any pre-defined building functions were meshed with a regular grid of evenly sized parcels. As a first approximation these parcels are taken to be quadratic. The parcels' alignment deviates about 32.1° from global north towards west.

Based on typical values identified for the building stock of Geneva (see section 6.4.1) the footprint of mixed-use buildings and single family houses (SFH) is assumed to be 250 m^2 and 125 m^2, respectively. Afterwards the parcel size was set to 1000 m^2, where each parcel is foreseen to host two buildings of the same type. Both these decisions were taken based on several considerations:

- This is this about the smallest size of existing adjacent parcels, which lie in the northeast of the new development (figure 6.1), and allows thus a continuous urban form.
- Both decisions reflect the targeted trade-off between spatial detail and computational tractability since one building per parcel would mean doubling the number of parcels.
- This parcel size allows to extend the model by the definition of typical office or commercial buildings which still would fit into a parcel each.

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- The resulting building area ratio of one parcel is 0.5 for mixed-use buildings and 0.25 for SFH, which is in line with common values for central and rural developments, respectively (Ruzicka-Rossier, 2005).

The chosen parcel size resulted in a separation of the case study area into 233 parcels.

6.2 Development project in Switzerland: "Les Palettes"

The model was adapted and extended to cope with development projects based on the project "Les Palettes". It was identified together with the project partners of the canton of Geneva. Although this is the name of a certain neighborhood, the project comprises as well the two adjacent neighborhoods "Les Semailles" in the north and "Le Bachet" in the east (figure 6.2). The project site lies about 1.5 km east of "Les Cherpines" and covers an area of approximately 50 ha housing about 10 000 inhabitants.

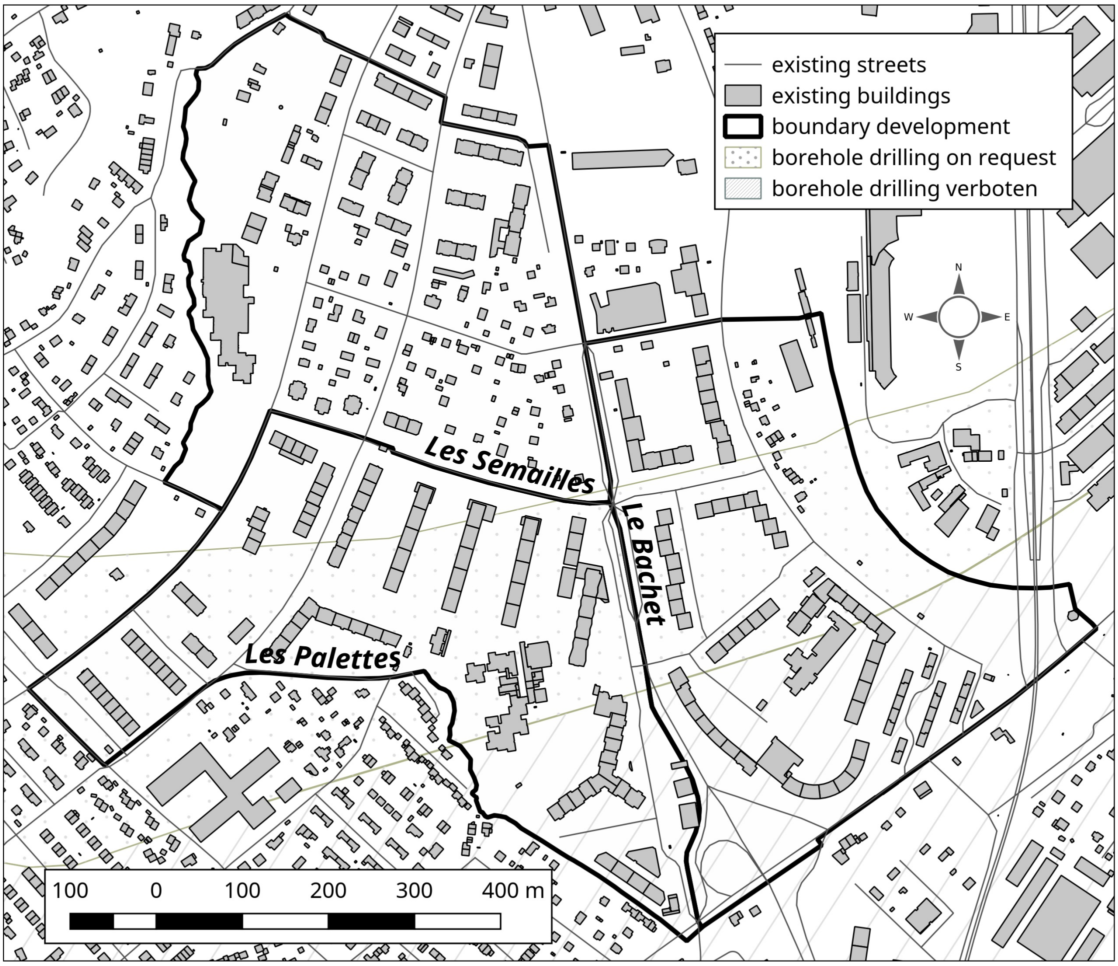

Figure 6.2 – Map of the case study "Les Palettes"

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Most of the data is available from the SITG, (1957): the planning project includes 428 buildings, which are mainly used for residential or partly residential purposes. Furthermore there are a number of buildings for educational purposes like schools and kindergartens. Figure 6.3 shows the distribution of building types. The category "other" comprises mainly garages and unclassified buildings of less than 20 m^2, which are excluded from the energy analyses for their non-existing or undefinable energy demands. The number of floors is available for 271 of the remaining 315 buildings.

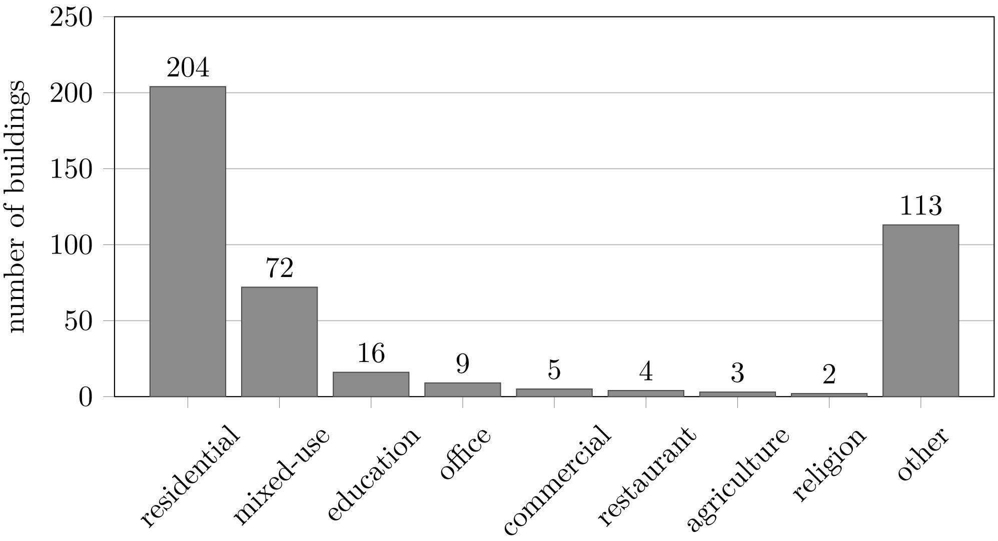


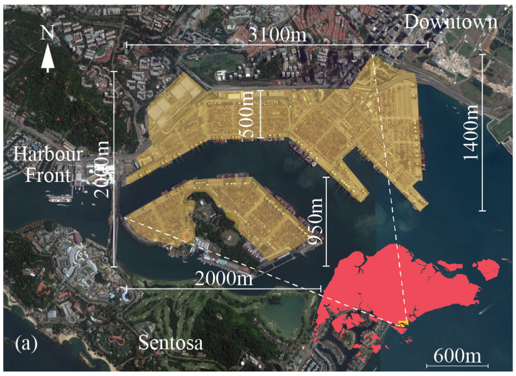
Figure 6.3 – Distribution of building types for the case study "Les Palettes"

Measurements of annual heat demand for both room heating and domestic hot water preparation are available for 151 buildings. The building parameters required as input for the multiple linear regression model presented in chapter 4 are available for 265 of the 271 buildings with floor information. Concerning the existing energy conversion systems, only information about installed boilers is available: of the 123 boilers in the planning perimeter, about 50.4 % are running with oil, 48.1 % are fueled by natural gas, and 1.5 % by wood. It is possible that some of these boilers supply several buildings each. However, this information is not extractable. Electric and gas networks are already in place so that no according investment costs have to be taken into account. Furthermore the installation of a new heating network is foreseen.

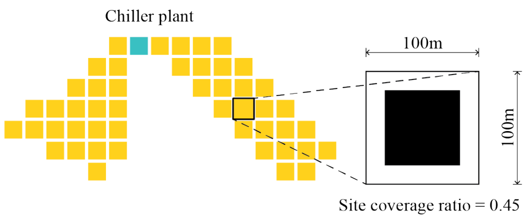
The planning zone is subject to several master plans from the cantonal level to the neighborhood level. The communal master plan of the according community "Lancy" states overarching objectives (Ville de Lancy, 2013): existing neighborhoods should be densified while preserving their social and functional variety. Densification is especially foreseen in form of the construction of new floors on top of existing buildings. The district should be further transformed to meet ecological standards by thermal refurbishment of buildings or replacement of existing energy conversion systems. In this context, a designated cantonal goal is to reduce the use of oil boilers. Decisions about densification and refurbishment have to respect the conservation of urban heritage. The communal master plan also lists a number of objects, mainly buildings, which characterize the neighborhoods, and whose visibility should thus be respected.

6.3 Redevelopment project in Singapore: "Tanjong Pagar"

The switch from greenfield planning to the development of existing city parts, as discussed in the previous section, is one potential change of context. Another one concerns the geographic location of the planning project, which influences physical conditions as meteorologic parameters, or political and legal conditions of the planning process. In order to account for such a change of context, a third case study is presented, which is a redevelopment project in Singapore named "Tanjong Pagar". The different boundary conditions consist in a much higher density compared to the Geneva case studies and furthermore in tropical weather conditions. The latter moves the focus on cooling technologies and their potential trade-offs with other urban aspects. Furthermore, the temporal scale is refined from 4 time steps as for the Geneva case studies, to 48 time steps depicting a typical tropical week day and weekend day. This refinement allows to assess the question for the need of shifting electricity produced by PV panels to hours of higher demand (see section 7.6.1).



(a) Arial photo indicating extensions of the case study



(b) Map indicating layout and extensions of the parcels and the building footprints

Figure 6.4 – Case study of "Tanjong Pagar" (Hsieh et al., 2017)

The authority of Singapore is planning to relocate the "Tanjong Pagar" container terminal freeing up an area of 200 ha for urban development (figure 6.4a). The site is located close to the the central business district and shall provide in future the major access to the sea from the city center. Due to its size, only a part of this case study is considered in this work, namely the Brani island. It is divided into 49 homogeneous quadratic cells of

1 ha each (figure 6.4b) with a site coverage ratio of 0.45. Similar to the case study of "Les Cherpines", residential, office, and commercial occupancy types are considered.

Since Singapore is located in the tropics, the annual meteorologic variation is neglected in comparison to the daily variation. The average hourly external temperatures and solar irradiation per skydome patch are calculated based on the EnergyPlus weather file for Singapore (EnergyPlus, n.d.). The respective hourly energy demand profiles for weekdays and weekend days are depicted in figure 6.5 (Duarte et al., 2016; Oh et al., 2016; Manandhar et al., 2015; Building and Construction Authority, 2016).

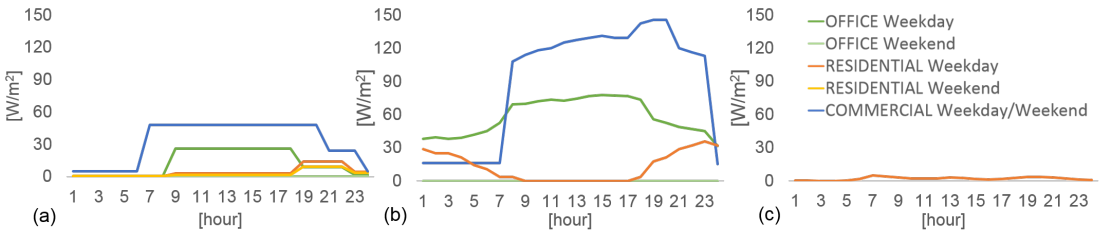


Figure 6.5 – Daily demand profiles for (a) electrical appliances and lighting, (b) cooling and (c) domestic hot water depending on day type and occupancy type (Hsieh et al., 2017)

Figure 6.6 provides an overview over the energy conversion and distribution systems considered for this case study. Due to the high air humidity, the cooling load in Singapore comprises a high latent heat ratio (40 %). This opens up the opportunity for a more efficient energy supply by using building cooling systems that apply the low-exergy concept (Schmidt, 2009). In these systems, the sensible and latent heat removal processes are respectively performed by radiant panels and condensing cooling coils with ventilation systems. The radiant panels can utilize chilled water at 19 °C instead of 8 °C, which could be supplied with high-temperature chillers at a better efficiency (Meggers et al., 2012). The high- and low-temperature chillers can be either installed in individual buildings or at centralized locations at the district level. The second option implies transport losses in the distribution network, while the first has the drawback that cooling towers are installed on the rooftops, which will limit the available area for PV panels to 60 % of the footprint of a building (Luther et al., 2013). If no cooling towers are installed, it is assumed that 100 % of the roof top area can be used for PV panels, as the roofs of high buildings are most often flat and the latitude of the site does not require to tilt the panels (section 6.4.3). Assumed efficiencies of energy conversion systems are identical to the case studies in Geneva (table 6.4). The last required input information concerns the share of RES of the national electricity supply of Singapore, which is almost negligible (Energy Market Authority, 2016).

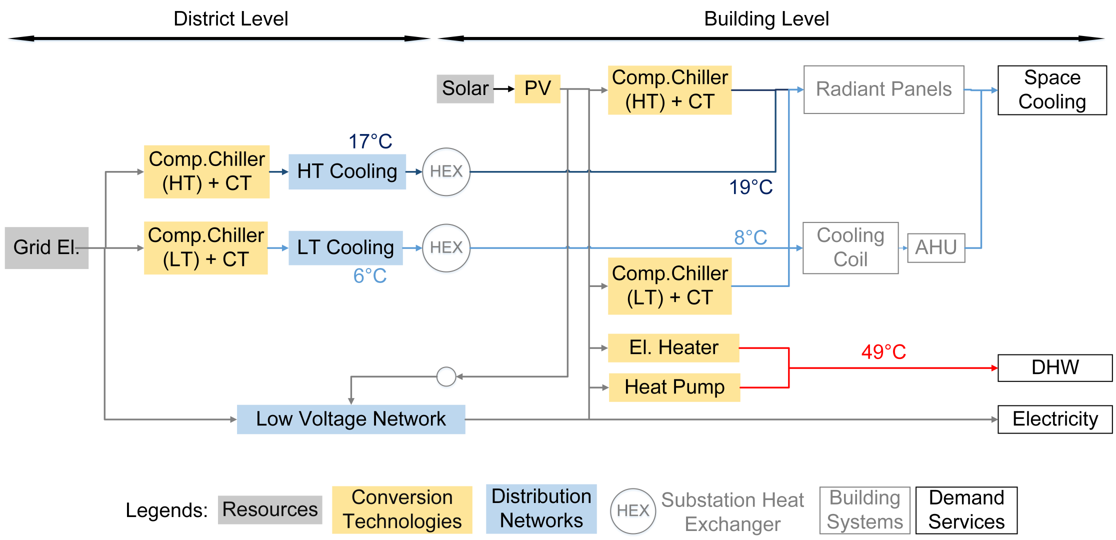


Figure 6.6 – Energy conversion pathways: the district level chillers at the centralized location are connected to cooling networks with two supply lines. (HT: High Temperature, LT: Low Temperature, CT: Cooling Tower, HEX: Heat Exchanger, DHW: Domestic Hot Water) (Hsieh et al., 2017)

6.4 Input data for the Geneva case studies

6.4.1 Urban form and function

Statistical analyses of the building stock of Geneva were carried out using data provided by (SITG, 1957) to identify representative values for parcel and building parameters. These values are especially relevant for the greenfield planning case in order to start from realistic assumptions where otherwise data is missing. The results are summarized in table 6.1.

Table 6.1 – Average values for form-related building parameters of the building stock of Geneva, for which the full set of listed parameters is available

Building function	buildings	floor height h_{fl} m	floors n_{fl}	footprint A_{fp} m^2
SFH	23954	4.1	2.29	113.8
MFH	8153	3.8	5.32	249.7
office	1182	4.8	4.35	655.2
commercial (excl. malls)	191	5.0	2.57	817.8

The permissible building height in the canton of Geneva is 21 m (Le grand conseil de la république et canton de Genève, 1988), which can be increased to 27 m to allow for an extra floor, if this floor is used for residential purposes.

6.4.2 Society

Table 6.2 lists assumed surface values related to residential use. An average gross floor area per job of $A_{\text{jobs}} = 30\,\text{m}^2$ was taken from (Rey and Lufkin, 2013).

Table 6.2 – Dwelling surface, occupancy rate and surface ratio for two building types

Building type	GFA/dwelling m^2	inhabitants/dwelling	ERA/GFA
MFH/mixed-use	100[a]	2.57[b]	0.84[d]
SFH	213[a]	2.85[c]	0.73[d]

[a] SITG, (1957), average values for the neighboring municipalities Confignon and Plan-les-Ouates
[b] OCSTAT, (2009a), values for the neighboring municipalities Confignon and Plan-les-Ouates
[c] OCSTAT, (2009b), values for the neighboring municipalities Confignon and Plan-les-Ouates
[d] Schneider et al., (2016)

Landmark View Factor

A mountain range named "Jura" lies in the north-west of Geneva. It's highest peak is "Cret de la Neige" at 1720 m and coordinates 2484462.5, 1125493.8 in the Swiss coordinate system CH1903+ / LV95 (EPSG:2056). The coordinates are used to calculate the distance to each building. The landmark's radius is taken as 9 km. It is further assumed that a floor is considered to have a view on a landmark if at least the uppermost 25 % of the landmark are visible.

6.4.3 Energy

Energy demand

The energy demand for four different categories of end use are considered: room heating, room cooling, hot water, and electricity for appliances, lighting and ventilation. Most of these demands are adapted from national norms specifying the demand of the different categories in dependence on building and/or occupancy type, building state (i.e. existing, refurbished, or new) and the according energy standard. Since some of these norms are not free of charge, table 6.3 indicates only the tables and pages of those norms containing the values used in this work.

Since a cantonal law forbids the cooling of surface of specific occupancy types, the room cooling demands of residential and educational floor areas are set to zero. Measurements of the annual heat demand for room heating and domestic hot water preparation are used

Table 6.3 – References and refurbishment factors for the estimation of energy demands

	unrefurb.	MoPEC 2014	MINERGIE-P
Annual demand			
room heating	sec. 4	a	= 0.7· MoPEC[b]
room cooling	c	d	d
hot water	sec. 4	d	d
electricity	c	d	d
Design demand			
room heating	e	f	f
room cooling	g	h	h
refurb. factor	–	1.5[a]	9/7[b]

[a] EnDK, (2014, p. 22)
[b] Minergie, (2017, p. 11)
[c] Schweizerischer Ingenieur- und Architektenverein, (2015, tab. 16): values “existing”
[d] Schweizerischer Ingenieur- und Architektenverein, (2015, tab. 16): values “standard”
[e] Girardin, (2012)
[f] EnDK, (2014, p. 22) where available, otherwise from Schweizerischer Ingenieur- und Architektenverein, (2015, tab. 11): values “standard”
[g] Schweizerischer Ingenieur- und Architektenverein, (2015, tab. 13)
[h] EnDK, (2014, p. 27)

for existing, unrefurbished buildings where available. Otherwise and if enough building parameters are available, the annual heat demand is estimated with the multiple linear regression model presented in chapter 4. Only if both is not the case, a building is not considered. Design heating demands are estimated using the energy signature model (Girardin, 2012) with the design temperature specified in table 6.5.

Supply temperatures of 12 °C for room cooling and 55 °C for domestic hot water preparation and room heating (Girardin, 2012, p. 78) were assumed to estimate coefficients of performance of chillers and heat pumps, respectively.

The requirements for thermal building refurbishments are usually less strict than the requirements for new buildings. The used Swiss norms account for this by a factor with which the limit for annual room heating demand of new buildings is to be multiplied (table 6.3). These refurbishment factors are used to estimate not only heating demands, but also cooling demands of refurbished buildings, although the latter is not specified by those norms.

Energy supply

For this work, only centralized CHP technologies are foreseen, while chillers and PV panels are installed only at the buildings. Boilers and heat pumps can be installed both centralized or decentralized. Two different annual efficiencies are used for heat pumps to account for higher efficiencies of larger, centralized technologies. Table 6.4 lists the different efficiencies for all considered energy conversion technologies.

Table 6.4 – Efficiencies of energy conversion technologies

Location	boiler			CHP[b]		heat pump		chiller[c]	PV[e]
	gas[a]	oil[a]	wood[a]			water-water[c]	air-water[d]		
	η_{th}	η_{th}	η_{th}	η_{th}	η_{el}	η_{COP}	η_{COP}	η_{COP}	η_{el}
decentral	0.9	0.85	0.85	–	–	0.5	0.34	0.40	0.16
central	0.95	0.873	0.864	0.46	0.44	0.6	0.38	–	–

[a] Moret, (2017)
[b] Voll, (2014)
[c] Henchoz, (2016)
[d] Girardin, (2012)
[e] Desthieux et al., (2014)

The assumptions regarding the estimation of PV potential include the conversion efficiency of the panels (see table 6.7), the available roof surface area for PV panels, the panels' tilt angle and the skydome. The roof surface can be partially shaded by roof superstructures such as chimneys or machine rooms for elevator systems. Furthermore, the roof surface available for PV panels might be reduced by windows. After a reduction of these factors, the remaining surface is still not equal to the collector surface, since in the case of flat roofs the panels should be mounted with a certain tilt angle to maximize the incident annual irradiation on the panels, depending on the geographical location. Consequently, it is assumed here that the PV panel area is 50 % of the footprint area. In addition, a panel tilt angle of 30° is taken (Desthieux et al., 2014, p. 19), that maximizes the annual solar irradiation exploitation for the latitude of Geneva.

In principle, a skydome containing the 145 sky patches of the Tregenza sky could be used to assess the solar potential. The piecewise linear formulation, however, requires a binary variable for each sky patch. Thus, the MILP problem would become quite large already for small numbers of parcels. This can be counteracted by disaggregating the sky vault into a smaller number of patches (figure 6.7).

Energy networks

Losses in the electric grid are assumed as 5 % of the supplied electricity (Best et al., 2015, p. 164), while losses in the gas grid are neglected (Keirstead et al., 2012, tab. 2).

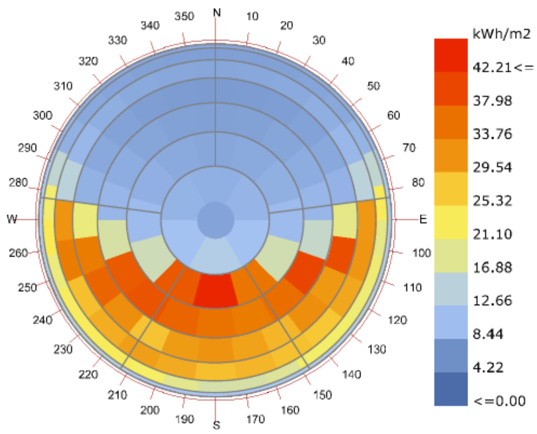


Figure 6.7 – Top view of a spheric skydome indicating the total annual irradiation on a surface tilted 30° towards south for the location of Geneva: aggregation into larger patches indicated by gray lines (cumulative sky created with Ladybug (Roudsari et al., 2013b))

Losses in the heating network are estimated as 4.3 % of supplied heat per km of network distance (Keirstead et al., 2012, tab. 2). Its nominal supply temperature is set to 60 °C at the heating center.

6.4.4 Environment

Table 6.5 lists the meteorologic parameters that influence the design of the energy conversion technologies. The EnergyPlus weather file available for Geneva is used to generate the cumulative sky (EnergyPlus, n.d.). Furthermore, a constant soil temperature of 10 °C is assumed (Weber and Shah, 2011).

Table 6.5 – Meteorologic parameters

		heating	cooling
design temperature[a]	°C	-7	30
average temperature[b]	°C	7.3	22.6
threshold temperature[c]	°C	16	18
annual duration[b]	h	6386	1755

[a] Henchoz, (2016)
[b] reference year 2016 Federal Office of Meteorology and Climatology, (2017)
[c] Girardin, (2012)

For the calculation of the RES shares on parcel and neighborhood scale, a RES share of 47.1 % for the Swiss supplier electricity mix is taken, considering only electricity from verifiable sources and further taking waste incineration as renewable (Frischknecht et al., 2012)

Environmental impact parameters, namely greenhouse gas emission and primary energy demand factors for the various energy carriers, are adapted from Schweizerischer Ingenieur- und Architektenverein, (2011, tab. A.1).

6.4.5 Economy

Assumed interest rates are: 1.7 % for owner-occupants (Nationalbank, 2017, reference year 2016), and 6 % for a local energy provider (OFEV, 2016).

Energy demand: refurbishment

Costs for refurbishments are estimated based on the values of Meier, (2015). These costs depend on the building type, the energy standard, and the refurbishment measure and are listed in table 6.6. The specified costs for multi family houses (MFH) are assumed for mixed-use and school buildings.

Table 6.6 – Costs for different refurbishment measures and energy standards

		MoPEC 2014	MINERGIE-P
SFH			
planning	CHF	8 000	18 000
roof	CHF/m^2	80	180
basement ceiling	CHF/m^2	80	150
façades	CHF/m^2	300	400
windows	CHF/m^2	800	1 000
MFH			
planning	CHF	40 000	90 000
roof	CHF/m^2	95	120
basement ceiling	CHF/m^2	85	100
façades	CHF/m^2	215	250
windows	CHF/m^2	720	800

Energy supply

An economic lifetime of 15 years is taken for all energy conversion technologies (Henchoz, 2016, p. 82). For the economic analysis, cost functions of several authors were compared. Non-linear cost functions are linearized with up to five segments where the choice of number and range of segments was made in order to achieve a good approximation of the original function. The resulting ranges, intercepts, and slopes of these segments are listed in table 6.7. A conversion factor of 1.1 $\frac{\text{CHF}}{\text{EUR}}$ is used for the costs of Voll, (2014) and Henchoz, (2016).

Table 6.7 – Linearized cost functions of energy conversion technologies

seg.	param.	unit	gas boiler[a]	oil boiler[c]	wood boiler[d]	CHP[a]	HP[b]	GSHP[b]	CH[a]	HTS[c]
	σ_{min}	kW_{th}	0	0	0	–	0	0	0	0
1	$c_{\text{inv,cst}}$	CHF	6694	6020	0	–	18501	38628	1181	658.7
	$c_{\text{inv,lin}}$	$\frac{\text{CHW}}{\text{kW}}$	220.2	242.5	494	–	2823.2	12085	274.7	73.5
	σ_{min}	kW_{th}	50	50	100	100	50	50	–	50
2	$c_{\text{inv,cst}}$	CHF	11150	10587	0	50045	31994	77473	–	1338
	$c_{\text{inv,lin}}$	$\frac{\text{CHW}}{\text{kW}}$	126.3	146.5	123	403.8	1701.3	8885.1	–	58.9
	σ_{min}	kW_{th}	100	100	–	500	100	100	–	100
3	$c_{\text{inv,cst}}$	CHF	23271	24065	–	103775	72066	232124	–	16355
	$c_{\text{inv,lin}}$	$\frac{\text{CHW}}{\text{kW}}$	46.5	58.9	–	294.6	671.1	5102.6	–	31.7
	σ_{min}	kW_{th}	1000	1000	–	1000	1000	1000	–	1000
4	$c_{\text{inv,cst}}$	CHF	53235	47270	–	166093	224108	78141	–	122825
	$c_{\text{inv,lin}}$	$\frac{\text{CHW}}{\text{kW}}$	17.4	32.8	–	234.9	204.6	3079.2	–	20.6
	σ_{min}	kW_{th}	5000	–	–	2000	–	5000	–	50000
5	$c_{\text{inv,cst}}$	CHF	88650	–	–	372960	–	1678988	–	315784
	$c_{\text{inv,lin}}$	$\frac{\text{CHW}}{\text{kW}}$	10.0	–	–	153.4	–	2332.0	–	16.8
	σ_{max}	kW_{th}	10000	2000	500	10000	10000	10000	100	125000

[a] Voll, (2014)
[b] Bochatay et al., (2005)
[c] Henchoz, (2016)
[d] Moret, (2017, sec. A.3), the reference size for decentralized wood boilers was increased from 10 to 100 $\frac{\text{CHW}}{\text{kW}}$

The same cost function is used for air-water heat pumps and water-water heat pumps, neglecting the additional costs of air-water heat pumps due to larger heat exchangers. The cost function for GSHP includes the costs for the geothermal probe. The cost function of Voll, (2014) for CHP technologies is extrapolated below 0.5 and above 3.2 MW. In order to convert the reference quantity of the cost function for heat exchangers given by Henchoz, (2016) from area to power, a heat transfer coefficient of 2.5 $\frac{\text{kW}}{\text{m}^2\,\text{K}}$ and an estimated logarithmic mean temperature difference of 5 K was used. For PV panels a fixed cost coefficient of 4000 $\frac{\text{CHF}}{\text{kW}_{\text{peak}}}$ is taken (Desthieux et al., 2014, p. 33).

Energy networks

Assumed prices depend on the energy carrier and the actors between which the carrier is traded. The prices are listed in table 6.8. The heat price at which the local supplier buys is the price for waste heat of the industrial zone and is assumed as 0.1 $\frac{\text{CHF}}{\text{kWh}}$

For the calculation of investment costs, an economic lifetime of 40 years is taken. Consequently, repeated investments in conversion technologies with lifetimes shorter than 40 years (see section 6.4.5) are taken into account for the calculation of e.g. the annual rate of return (Henchoz, 2016, p. 82). If a new gas grid has to be installed, the

Table 6.8 – Energy prices in $\frac{\text{CHF}}{\text{kWh}}$

resource	nat. ↔ loc. supplier	loc. supplier → end user	end user → loc. supplier
electricity	0.1056[a]	0.2076[b]	0.0944[b]
gas	0.0602[c]	0.0844[d]	–
heat	–	0.15	–
oil	0.08655[e]	0.08655[e]	–
wood chips	0.065[f]	0.065[f]	–

[a] Moret et al., (2016, sup. mat., tab. 4)
[b] Eidgenössische Elektrizitätskommission, (2016)
[c] Moret et al., (2016)
[d] Eidgenössisches Departement für Wirtschaft, Bildung und Forschung, (2016): consumer category IV – multi-family housing, average demand 100 000 kWh/a, heating and DHW
[e] Moret, (2017, tab. D3), local suppliers are assumed to only buy from national suppliers and not sell
[f] ForêtSuisse, (2017), local suppliers are assumed to only buy from national suppliers and not sell

related investment costs are estimated with a factor of 375 $\frac{\text{CHF}}{\text{m}}$ based on (Keirstead et al., 2012, tab. 2). To estimate the investment costs for a new heating network the cost function of Henchoz, (2016, tab. 1.12) is used with a length and diameter specific cost factor of 5670 $\frac{\text{CHF}}{\text{m}^2}$ and a length specific cost factor of 613 $\frac{\text{CHF}}{\text{m}}$. An average diameter of the network pipes of 0.15 m is assumed based on existing networks in comparable neighborhoods. The resulting length specific costs are in the range of the costs given by Keirstead et al., (2012, tab. 2).

Chapter 7

Demonstration

Highlights

This chapter demonstrates ...

Phases	... the capability of the developed planning support system to show the interdependency between decisions
Domains	... the answers to different planning questions concerning urban form and function, environment, energy, society, and costs
Scales	... results on district and building scales
Contexts	... results for three different case studies
Actors	... the influence of the considered actor(s) on the outcomes
Ranges	... the influence of the considered spatial range on the outcomes
Uncertainty	... the influence of uncertain parameters on the outcomes

The results presented in sections 7.1, 7.3, 7.4 and 7.5 are based on material first published in (Schüler et al., 2018b). The contents of section 7.6.1 were first published in (Hsieh et al., 2017) and the results described in section 7.6.2 are to be published in (Schüler and Cajot, 2018b).

7

This chapter contains outputs that are obtainable by using URB^{io} . It is organized according to the different aspects of urban complexity, whose capturing the results shall demonstrate. All optimization runs presented in this chapter were solved using CPLEX 12.6 (CPLEX 2014) with an optimality gap limit of 1 %. Most of the results in this chapter are represented in form of parallel coordinates, which are a convenient way to represent multi-dimensional information (Cajot et al., 2018).

7.1 Phases

The first goal is to demonstrate the developed computational framework's ability to integrate planning phases by showing the impact of decisions made during this phase on decisions made during the design phase, often by different actors. The insights gained this way allow to adapt the decisions in the planning phase in order to define realistic planning goals and to make the achievement of planning goals lying in the interest of every actor.

This is demonstrated on the basis of the case study "Les Cherpines" (section 6.1) by asking the following question: what are the implications of the decisions of the planners regarding density and environmental targets on design decisions regarding the energy supply and distribution system, assuming that the latter are utterly driven by economic interest? The system boundary of this analysis is thus drawn around the whole neighborhood, while still regarding the system in detail (see section 7.3).

The density target consists in the FAR that the new neighborhood should have, and the environmental target is the share of RES that the installed energy supply and distribution system shall achieve. These two indicators form thus the decisions of the planners θ in equation (2.2) and their values are varied systematically to capture the according decision space. This question can be translated into the following optimization problem:

$$\begin{aligned} \min \quad & \sum_{pc}\sum_{et}\sum_{cb}\left(af^{cb,et}\cdot \boldsymbol{C}_{\mathbf{inv}}^{cb,pc,et} + \boldsymbol{C}_{\mathbf{op}}^{cb,pc,et}\right) \\ \text{subject to} \quad & FAR_{\min} \leq \boldsymbol{FAR} \\ & s_{\text{res,min}} \leq \boldsymbol{s}_{\mathbf{res}} \\ & \boldsymbol{s}_{\mathbf{gfa}}^{\text{off}} \geq 0.3 \\ & \boldsymbol{s}_{\mathbf{gfa}}^{\text{com}} \geq 0.025 \end{aligned} \tag{7.1}$$

This problem is generated by converting a multi-objective optimization problem into a single-objective optimization problem as explained in section 2.2. Figure 7.1 shows the decision space of the planners that was captured by solving the above stated optimization problem. On the second and third axes the decision variables of the planners are plotted, one out of the social domain with the FAR, and the other out of the environmental domain with share of RES. The impact on design decisions is represented in form of total costs of the energy system on the first axis and the connection rate to the heating network on the fourth axis.

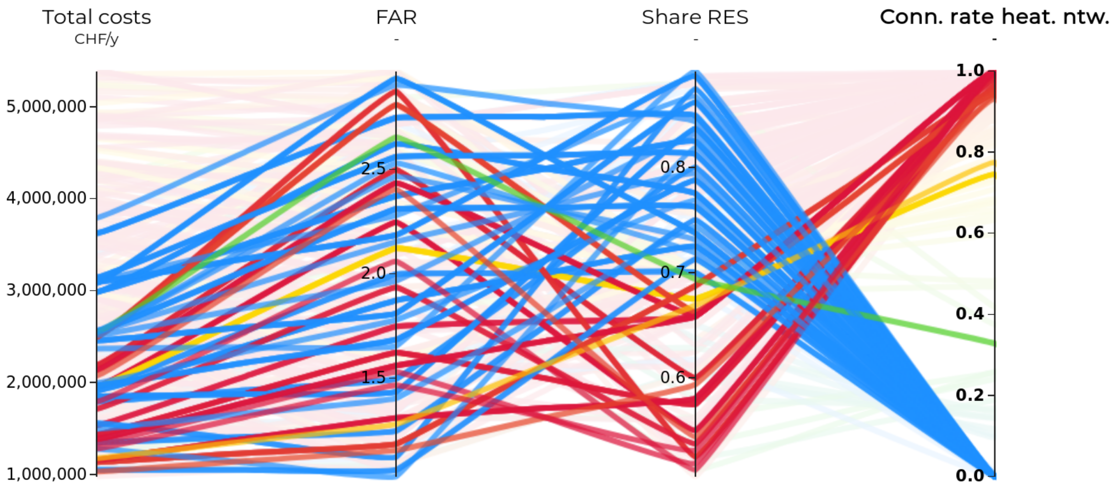
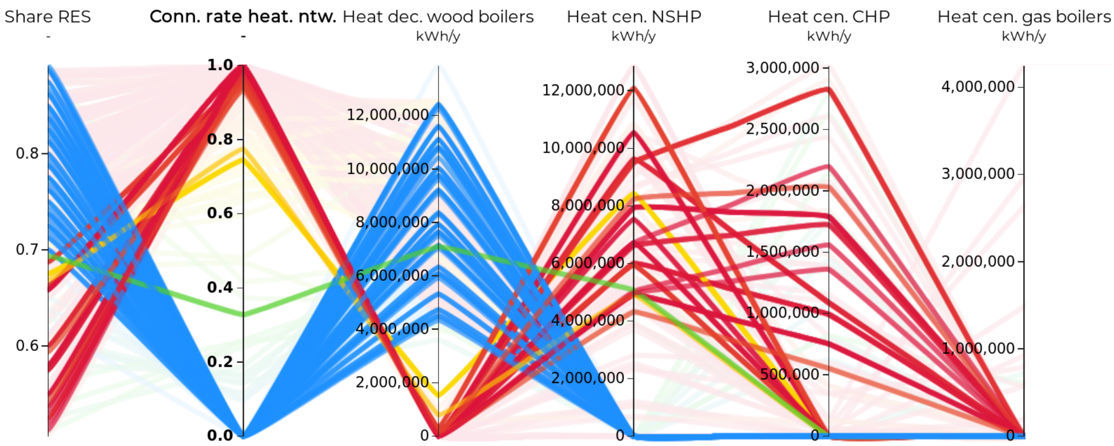


Figure 7.1 – Impact of planning decisions regarding density and share of RES on selected indicators for costs and energy system (colored by connection rate): the environmental target influences which energy supply system is economically the most favorable.

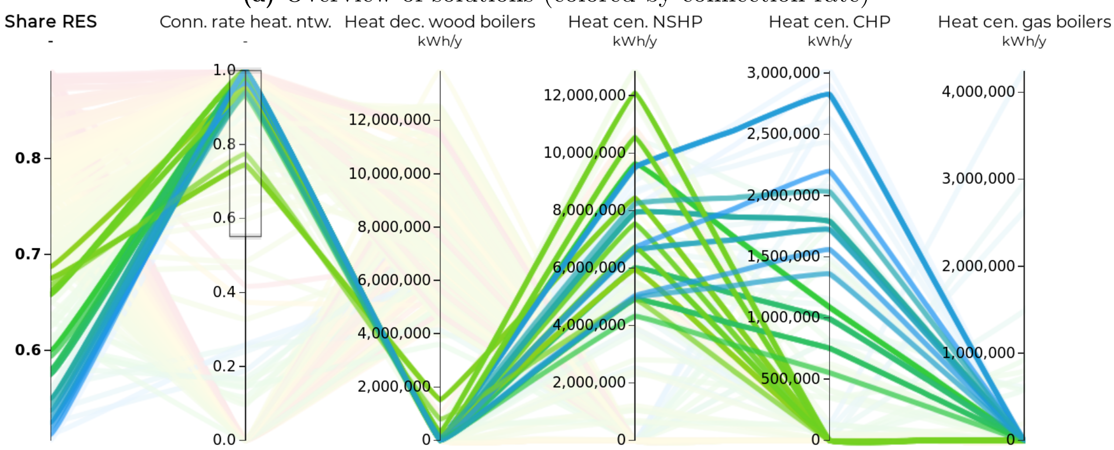
The parallel coordinate plot reveals that an increasing share of RES leads to a decrease in the connection rate. The zone in which this transition is happening is around a share of RES of 69 % and furthermore relatively small. It is further notable that the connection rate is independent of the density. Analyzing the slopes of the red lines, which indicate the choice of a centralized system, between the axes of total costs and FAR, it is deducible that an increasing FAR implies a sublinear increase in total costs for centralized systems. The both last observations will be addressed in section 7.3.

Figure 7.2a shows that in case of a decentralized energy supply system, heat is mainly coming from wood boilers. In case of a centralized system, heat is supplied by following conversion systems, ordered by their annual output: a heat pump using industrial waste heat, a CHP facility and/or a boiler, both fueled by natural gas. Figure 7.2b reveals also that the lower the constraint on share of RES is, the more energy is supplied by the conversion systems running on natural gas.

Transitions and tipping points are characteristic for complex systems as described in section 1.1.1. Overall, it can be concluded that there is indeed a tipping point in the analyzed decision space, as the decision for an environmental target in form of a minimum share of RES for the new neighborhood has an impact on the choice and design of the energy supply system. The observed transition is the change from a centralized system to a decentralized system which implies a substitution of a heat pump using the waste heat of a neighboring industrial zone, by decentralized wood boilers. This transition could, however, have its disadvantages since it implies, for example, an increase in local air pollution from the burning of wood. Hence it is of interest to understand what is happening at this tipping point and how its appearance can be influenced. This analysis starts with determining the influence of input parameters on the obtained outcomes.



(a) Overview of solutions (colored by connection rate)



(b) Focus on solutions with a centralized energy system: dependence on share of RES (colored by share of RES)

Figure 7.2 – Annual heat supplied by the different energy supply systems in dependence on connection rate

7

7.2 Uncertainty

The method of multi-parametric programming, as explained in chapter 2, allows to not only vary the right-hand side (RHS) parameters of constraints for multi-objective optimization (section 7.1), but also comprises a variation of the left-hand side (LHS) parameters, i.e. the coefficients in V and W of the constraints in equation (2.3) (Oberdieck et al., 2016). The variation of the latter allows to perform sensitivity analyses on all kind of parameters, which can be used to assess the uncertainty of input parameters. An example is presented that shows the impact of an uncertain parameter on the decisions concerning the energy system design of the new neighborhood.

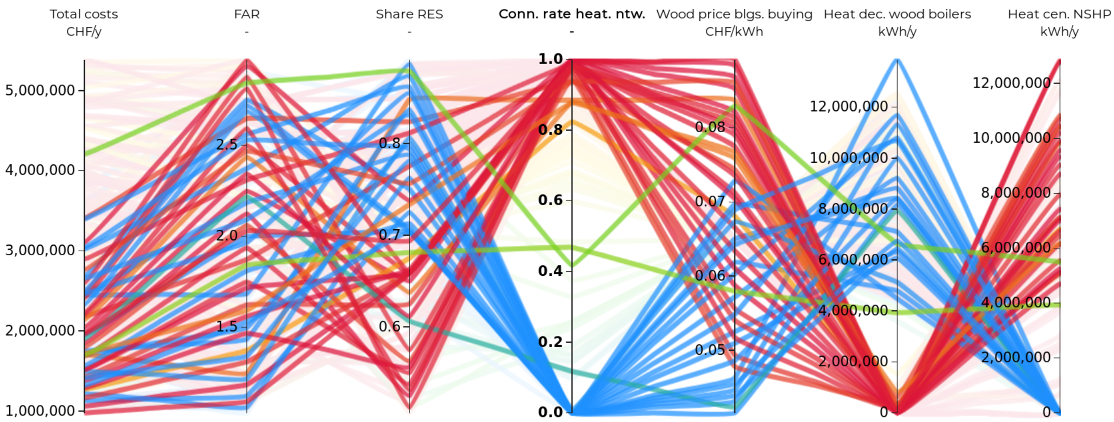
7.2.1 Price of wood pellets

As the centralized energy system gets at a certain point economically less favorable than a decentralized energy system based on wood boilers, the question arises about the impact of the wood pellet price on this tipping point. An according optimization problem could be:

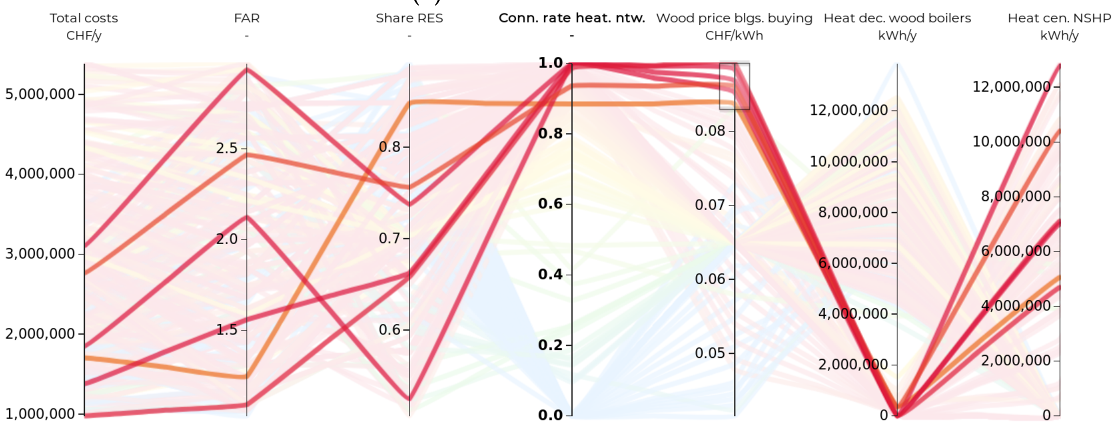
$$\begin{aligned}
\min \quad & \sum_{pc}\sum_{et}\sum_{cb}\Big(af^{cb,et}\cdot \boldsymbol{C}_{\mathbf{inv}}^{cb,pc,et} + \boldsymbol{C}_{\mathbf{op}}^{cb,pc,et}(pr_{\text{wood}})\Big) \\
\text{subject to} \quad & FAR_{\min} \leq \boldsymbol{FAR} \\
& s_{\text{res,min}} \leq \boldsymbol{s}_{\mathbf{res}} \\
& \boldsymbol{s}_{\mathbf{gfa}}^{\text{off}} \geq 0.3 \\
& \boldsymbol{s}_{\mathbf{gfa}}^{\text{com}} \geq 0.025
\end{aligned} \tag{7.2}$$

Figure 7.3 shows the sampled solutions to that optimization problem. It reveals a transition zone above which a centralized energy system (figure 7.3b) and below which a decentralized energy system is most favorable for any configuration in terms of density and share or RES (figure 7.3c). This transition zone lies between wood pellet prices of $0.073\,\frac{\text{CHF}}{\text{kWh}}$ and $0.048\,\frac{\text{CHF}}{\text{kWh}}$. In case of a centralized system, heat is again mainly supplied from a heat pump using industrial waste heat.

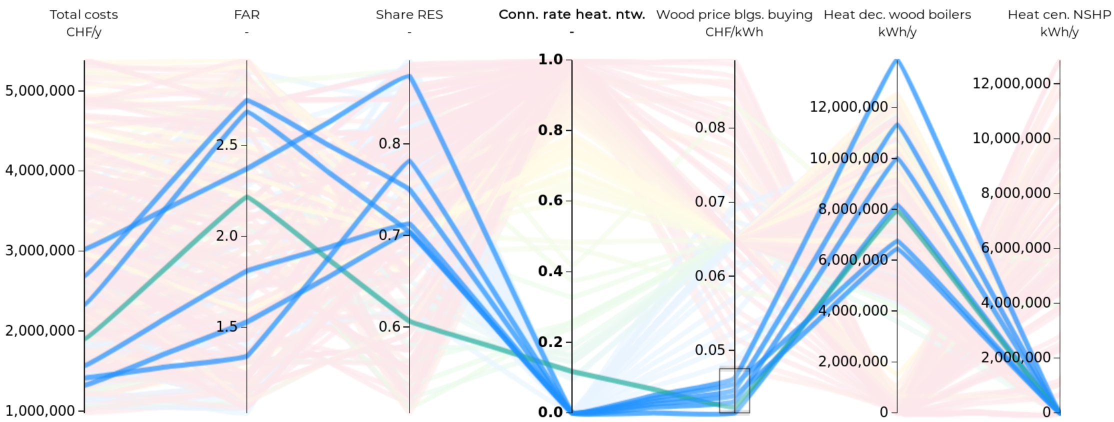
Taking into account that wood pellet prices are relatively stable, with variations of about $\pm 15\,\%$ in the last 10 years (Forever Fuels, 2016), and that the assumed wood pellets price of $0.065\,\frac{\text{CHF}}{\text{kWh}}$ (table 6.8) is rather at the upper end of the zone, a moving of the tipping point between a centralized and decentralized system due to the development of wood pellets prices is not so likely, but if so than in favor of a centralized system.



(a) Overview of solutions



(b) Focus on high wood pellets prices: a centralized energy system is the most favorable regardless the share of RES



(c) Focus on low wood pellets prices: a decentralized energy system is the most favorable regardless of the share of RES

Figure 7.3 – Impact of wood pellets price on connection rate (colored by connection rate)

7.3 Scales

So far most of the observations could be explained by analyzing the results on a neighborhood scale. This might raise the question about the advantages of or the requirement for accounting for multiple scales within modeling for urban planning, which will be demonstrated by the following example.

7.3.1 Heating network connection vs. building distribution

Two observations have been made in section 7.1: (i) the connection rate is independent of the density and (ii) an increasing density implies an sublinear increase in total costs for centralized systems. In order to interpret these, a further axis is added to the parallel coordinates plot of figure 7.1: the standard distance indicates the degree to which the features are scattered around their geometric mean center (section 3.1.7). When applying it to buildings it can be used as a criterion for urban form. It is thus only derivable when accounting for each building's location in a model.

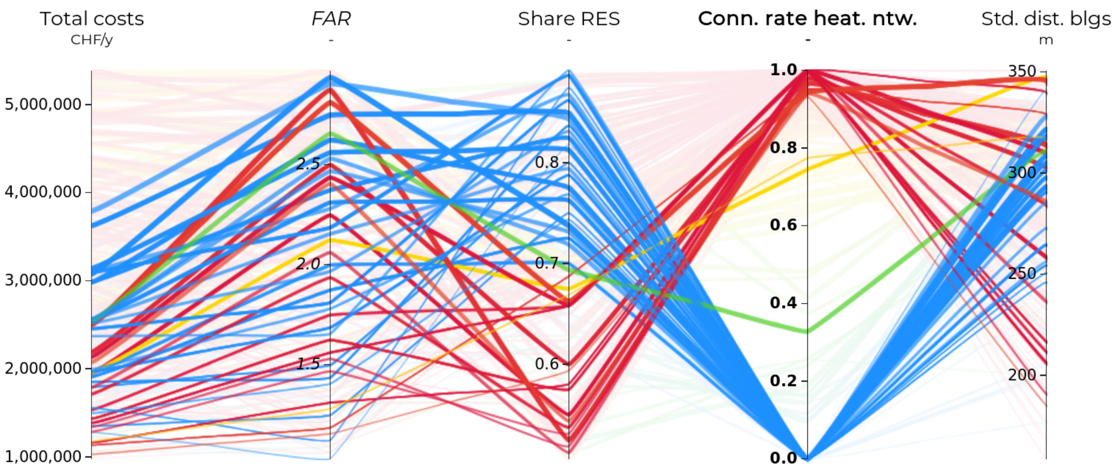


Figure 7.4 – Standard distance of buildings in dependence on connection rate (colored by connection rate, line thickness increasing with FAR): lower standard distance in case a centralized energy system is chosen.

Figure 7.4 shows that the standard distance is negatively correlated with the connection rate. Although this is already an indicator that buildings are more scattered in case of a decentralized energy supply system, it remains quite abstract. The meaning of it might become clearer when looking at maps of selected solutions (figure 7.5).

The map in figure 7.5c shows that for the case of all buildings being connected to the heating network, they are clustered in the southern edge i.e. close to the connection to the neighboring industrial zone. Since the optimization problem (7.1) does not comprise any further constraint influencing the allocation of buildings, network-related investment costs can thus be greatly minimized. This effect happens independently from the constraint on

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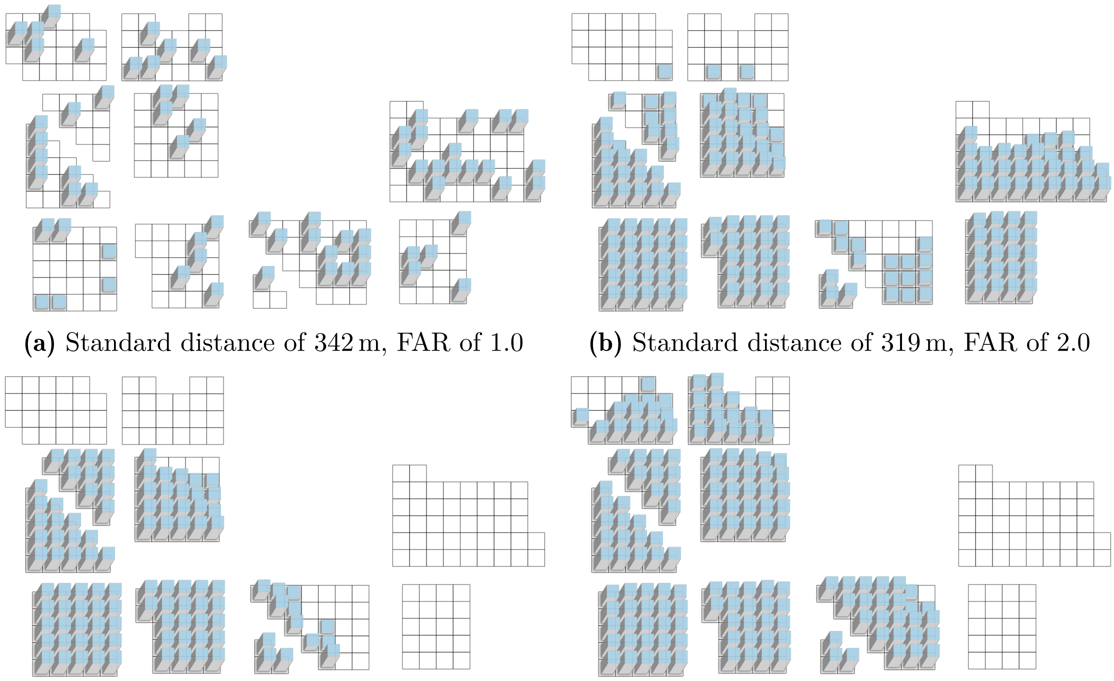


(a) Standard distance of 342 m, FAR of 1.0

(b) Standard distance of 319 m, FAR of 2.0

(c) Standard distance of 191 m, FAR of 1.5

(d) Standard distance of 237 m, FAR of 2.1

Figure 7.5 – Maps showing the distribution of buildings for selected solutions

minimum density (figure 7.5d). Consequently, although an increase in density implies an increase of both the standard distance of buildings and of the overall network length and the corresponding investment costs, this increase is as small as possible and compensated by revenues from additional sales of heat. Thus the connection rate was not found to be dependent on density (figures 7.1 and 7.4).

Moreover, the more buildings get connected, the higher are the investment costs for the initial network pipes bridging the distance between the industrial zone and the perimeter of the neighborhood compensated by additional heat sales. Consequently, the total costs for centralized systems increase sublinearly with increasing density. In case of a decentralized energy system, the optimization problem does not comprise any terms in neither the objective function nor the constraints that would render one allocation of buildings better than another. Thus the buildings are scattered randomly over the planning site (figure 7.5a).

After assessing the results on a finer scale, namely the building scale, it can be concluded that the tipping point identified in section 7.1 does not only concern the energy system but also the urban form.

7.4 Actors

Section 7.2 revealed the wood price as one factor influencing the tipping point that was identified in section 7.1. However, it is not a factor that the actors within the planning project can necessarily influence. This section will bring up a factor which is indeed influenceable by them.

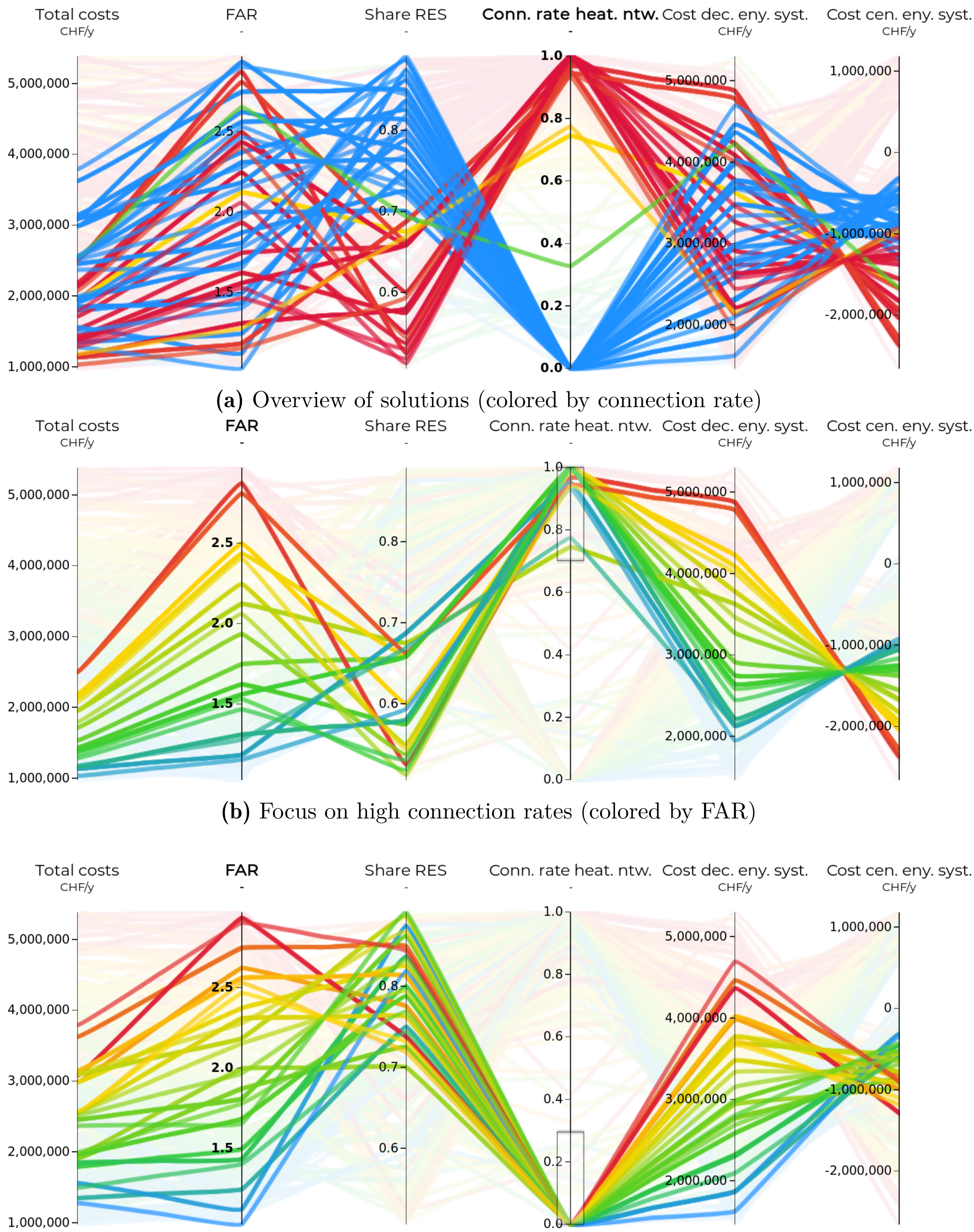
So far the actors were regarded as one group with a common interest, namely the minimization of their total costs (equation 7.1). This, however, is a simplification and can have undesired effects. Consequently, the developed optimization model allows to account separately for the costs of different actors by the means of cost balances (section 3.5).

Two types of actors are affected by the stated problem: the first are the owner-occupants of the buildings, who are assumed to form one homogeneous group Accordingly, the assumption is made that all buildings are occupied by their owners and no conflict of interest exists as might be the case for landlords and tenants. This means that the annualized investment cost and annual operation cost for the energy supply are paid by the same actor. The second actor considered is the local energy supplier whose task it is to provide the energy infrastructure consisting in networks and centralized conversion systems. Similar to the group of owner-occupants, it is assumed that the supplier follows an economic interest.

Figure 7.6 displays the solutions of figure 7.1 with two additional criteria: the costs of owner-occupants (dec. eny. syst.) and the costs of the local energy provider (cen. eny. syst.). It can be observed first that, in general, the higher the costs of owner-occupants are, the more negative are the costs of the provider (i.e. the higher are their profits). But more importantly, the plot reveals the distribution of costs or profits, respectively, between the two actors: a decentralized energy system implies less costs for building owners but also less profits for the energy provider than for cases of a centralized energy system. Following this, the tipping point at a share of RES of 69 % also concerns the cost distribution between the actors.

Figure 7.6b shows that the costs of building owners and profits of the provider, respectively, increase only with density for a decentralized system and low shares of RES. In the case of centralized systems (figure 7.6c), the costs increase mainly with density but are also affected by the share of RES, hinting that there are further tipping points of the energy system within this range.

The identified effect of the tipping point leads to question the fairness of the distribution of costs or profits, respectively, if just the total costs of all actors are minimized.



(a) Overview of solutions (colored by connection rate)

(b) Focus on high connection rates (colored by FAR)

(c) Focus on lowest connection rate (colored by FAR)

Figure 7.6 – Cost of building owner-occupants (dec. eny. syst.) and local energy provider (cen. eny. syst.) in dependence on connection rate

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7.4.1 Building owners

To assess this question, the economic interest of building owner-occupants is analyzed in a first step. Therefore, an optimization problem is formulated minimizing their total energy-related costs:

$$\begin{aligned} \min \quad & \sum_{pc} \sum_{et} \left(af^{\text{ow-oc},et} \cdot \boldsymbol{C}_{\mathbf{inv}}^{\text{ow-oc},pc,et} + \boldsymbol{C}_{\mathbf{op}}^{\text{ow-oc},pc,et} \right) \\ \text{subject to} \quad & FAR_{\min} \leq \boldsymbol{FAR} \\ & s_{\text{res,min}} \leq \boldsymbol{s}_{\mathbf{res}} \\ & \boldsymbol{s}_{\mathbf{gfa}}^{\text{off}} \geq 0.3 \\ & \boldsymbol{s}_{\mathbf{gfa}}^{\text{com}} \geq 0.025 \end{aligned} \tag{7.3}$$

Figure 7.7 shows the resulting solutions to this problem. It reveals that the heating network connection rate is always high. However, the heat supplied by the network to the buildings is about three orders of magnitude smaller than the heat supplied by decentralized wood boilers. This indicates that the heating network is only used for peak loads. Furthermore, it stands out that the resulting minimum share of RES is about 70 %, although the shares were varied between 50 % and 90 % as for the previous problems. The reason is again the utilization of wood boilers to cover the base load, which brings along high shares of RES.

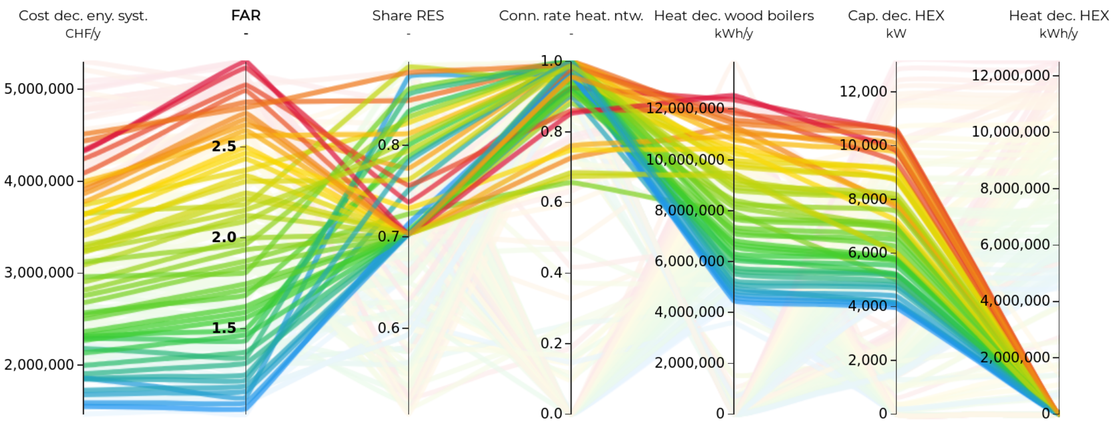

Figure 7.7 – Solutions for the minimization of costs of building owner-occupants (colored by FAR)

From this an intermediate conclusion is that it would be indeed beneficial for both building-owners and the advance of renewable energy to install wood boilers and use a heating network just to cover peak loads. Nevertheless, this is not likely to be in the

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interest of the local energy provider. Consequently, it is important to also include their economic interest in the problem formulation.

7.4.2 Building owners and energy provider

Based on this insight, equation (7.3) is extended by an constraint to allow only supply options that guarantee the local energy provider a certain annual rate of return (here 6 %):

$$\begin{aligned} \min \quad & \sum_{pc} \sum_{et} \left(af^{\text{ow-oc},et} \cdot \boldsymbol{C}_{\mathbf{inv}}^{\text{ow-oc},pc,et} + \boldsymbol{C}_{\mathbf{op}}^{\text{ow-oc},pc,et} \right) \\ \text{subject to} \quad & FAR_{\min} \leq \boldsymbol{FAR} \\ & s_{\text{res,min}} \leq \boldsymbol{s}_{\mathbf{res}} \\ & \boldsymbol{s}_{\mathbf{gfa}}^{\text{off}} \geq 0.3 \\ & \boldsymbol{s}_{\mathbf{gfa}}^{\text{com}} \geq 0.025 \\ & 0.06 = RR_{\min} \leq \frac{-\boldsymbol{C}_{\mathbf{op}}^{\text{les},et}}{\sum_{et} \boldsymbol{C}_{\mathbf{inv}}^{\text{les},et} + \boldsymbol{C}_{\mathbf{inv,ntw}}} \end{aligned} \tag{7.4}$$

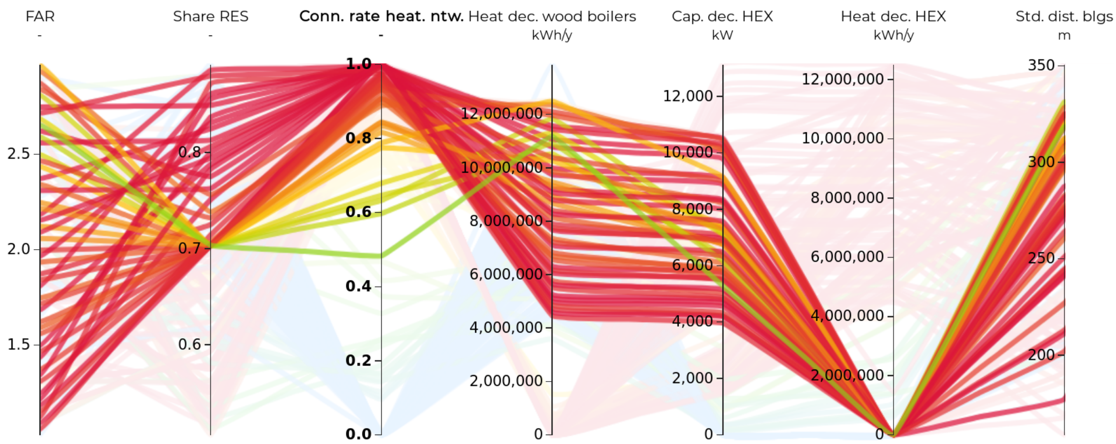


Figure 7.8 – Solutions for the minimization of costs of building owner-occupants, while constraining the return rate of the local energy provider (colored by connection rate)

Figure 7.8 shows that the connection rate is more or less negatively correlated with both density and the standard distance of buildings. This indicates that it is required to connect a certain amount of buildings to justify the investment costs in the heating network and that these buildings should have to be clustered around the heating network connection. However, despite of the additional constraint on the return rate of the local energy provider, the heating network is still mainly employed for peak loads. This means that the energy provider can make enough profit at the assumed prices to provide the option of a heating network. Nevertheless, this would be a very unusual exploitation of a heating network and surely not the most attractive business case for the local energy provider. Thus, if sticking with the overall objective of minimizing the energy-related costs of building-owners, a goal could be to make it more attractive for buildings to use heat from the network to also cover their base load. A handle to achieve this consists in the price at which they buy heat from the local provider. Lowering this price should make the centralized option more attractive for buildings.

7.4.3 Influence of heat price

The according optimization problem is:

$$\begin{aligned}
\min \quad & \sum_{pc}\sum_{et}\left(af^{\text{ow-oc},et}\cdot \boldsymbol{C}_{\mathbf{inv}}^{\text{ow-oc},pc,et} + \boldsymbol{C}_{\mathbf{op}}^{\text{ow-oc},pc,et}(pr_{\text{heat}})\right)\\
\text{subject to} \quad & FAR_{\text{min}} \leq \boldsymbol{FAR}\\
& s_{\text{res,min}} \leq \boldsymbol{s}_{\mathbf{res}}\\
& \boldsymbol{s}_{\mathbf{gfa}}^{\text{off}} \geq 0.3\\
& \boldsymbol{s}_{\mathbf{gfa}}^{\text{com}} \geq 0.025\\
& 0.06 = RR_{\text{min}} \leq \frac{-\boldsymbol{C}_{\mathbf{op}}^{\text{les},et}(pr_{\text{heat}})}{\sum_{et}\boldsymbol{C}_{\mathbf{inv}}^{\text{les},et} + \boldsymbol{C}_{\mathbf{inv,ntw}}}
\end{aligned} \tag{7.5}$$

Figure 7.9 demonstrates that there exists indeed such a tipping point, at which the heating network also becomes the economically most favorable option to cover the base load of the buildings, replacing the formerly installed wood boilers. This transition appears between a heat price of 0.08 $\frac{\text{CHF}}{\text{kWh}}$ and 0.083 $\frac{\text{CHF}}{\text{kWh}}$. This information could be used to settle a heating price that is attractive for all considered actors.

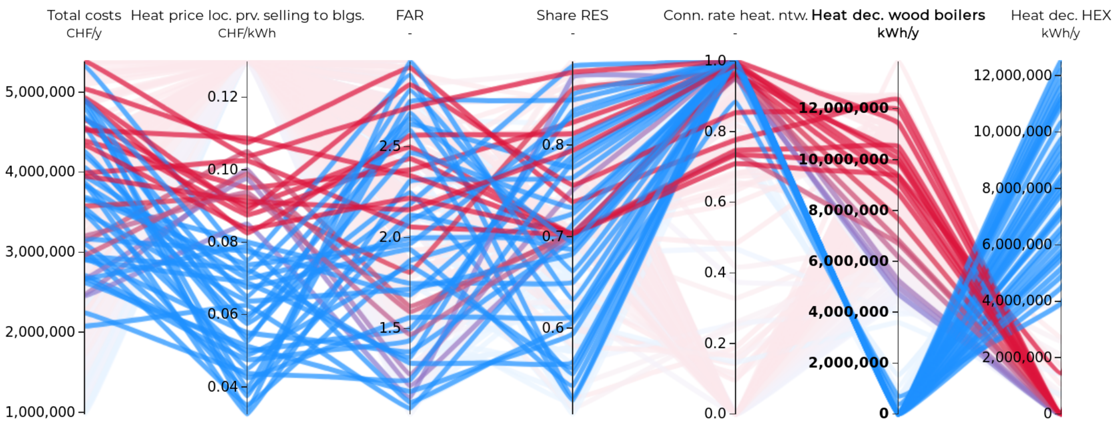


Figure 7.9 – Tipping point between the heating network covering peak load only and covering also base load triggered by a variation of the heat price (colored by heat price)

Nevertheless, it is remarkable that this price range is well below reported heat prices of some heating networks recently installed in Switzerland (Henchoz, 2016). An explanation therefore is the formulation of the optimization problem, which allowed the allocation and sizing of buildings as to minimize the investment costs for the heating network. However, the maps presented in section 7.3 revealed that the resulting urban form is not necessarily attractive. Consequently, social aspects are considered in the following.

7.5 Domains

7.5.1 Society

If the involved stakeholders acted strictly economically driven, the previously identified plans would best reflect their interests. However, these plans are not attractive under other considerations since a densely clustered, high-rise environment is likely to not be considered very livable by most occupants. One implication of such dense plans is that open spaces are not nearby or even entirely missing. A further implication is that the view on e.g. surrounding landmarks is very limited. Such a view influences in turn the prices of buildings or flats within these buildings, at which building contractors can sell them to owner-occupants (Benson et al., 1998; Thalmann, 2010). Inspired by these shortcomings, a second principal question aims at social aspects rather than the energy system and its economic and environmental effects: what are the implications of the decisions of the planners regarding density and park targets on the resulting urban form, assuming that the building contractors try to maximize the view of all buildings? The resulting optimization problem is:

$$\begin{aligned} \max \quad & \sum_{pc} \boldsymbol{n}^{pc}_{\mathbf{fl,view}} \\ \text{subject to} \quad & FAR_{\min} \leq \boldsymbol{FAR} \\ & s_{\text{park,min}} \leq \frac{\sum_{pc} \boldsymbol{\xi}^{pc}_{\mathbf{park}} \cdot A^{pc}_{\text{par}}}{\sum_{pc} A^{pc}_{\text{par}}} \end{aligned} \tag{7.6}$$

In order to respect the conditions for livable parks (section 3.2.1), it is assumed that parks are surrounded by at least five buildings (equation 3.15), which in total comprise a minimum of three residential floors, two office floors and one commercial floor (equation 3.16), and which are not further away than 50 m. Besides that, parks shall have a minimum annual solar irradiation of 500 $\frac{\text{kWh}}{\text{m}^2\,\text{a}}$ (equation 3.17).

Figure 7.10 shows the considered criteria, this time in a 3D plot, to illustrate the decision space for planners. The surface spanning up this space is of triangular shape, which is due to the existence of a maximum achievable share of parks for a given density. It can be further noted that the achievable LVF increases with decreasing FAR and decreasing

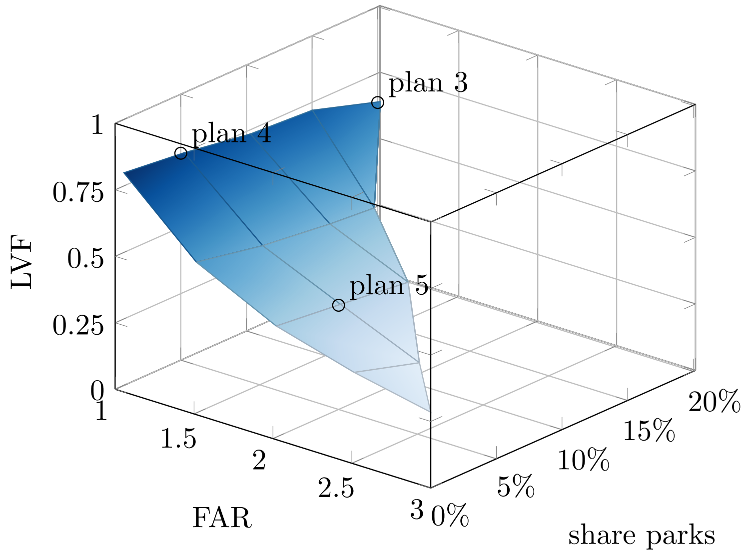
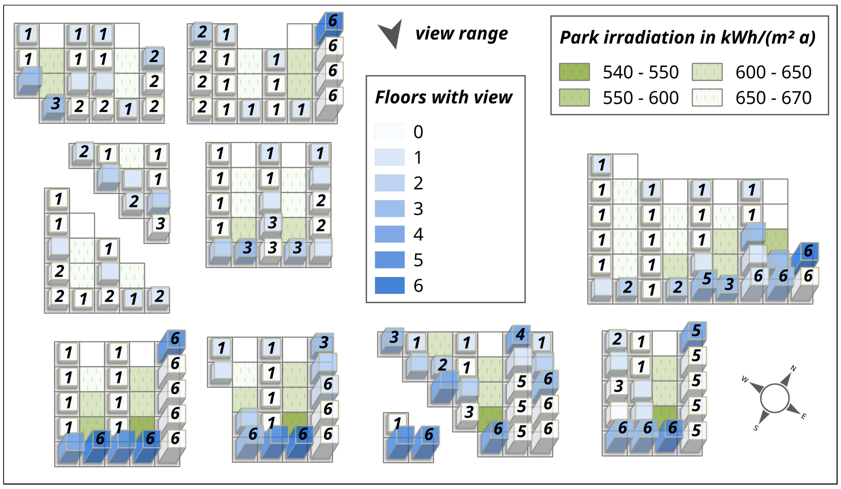


Figure 7.10 – Capturing the decision space for planners: their decisions on density and share of parks influence the maximum achievable LVF (circles indicate plans that are presented in more detail in section 7.11).

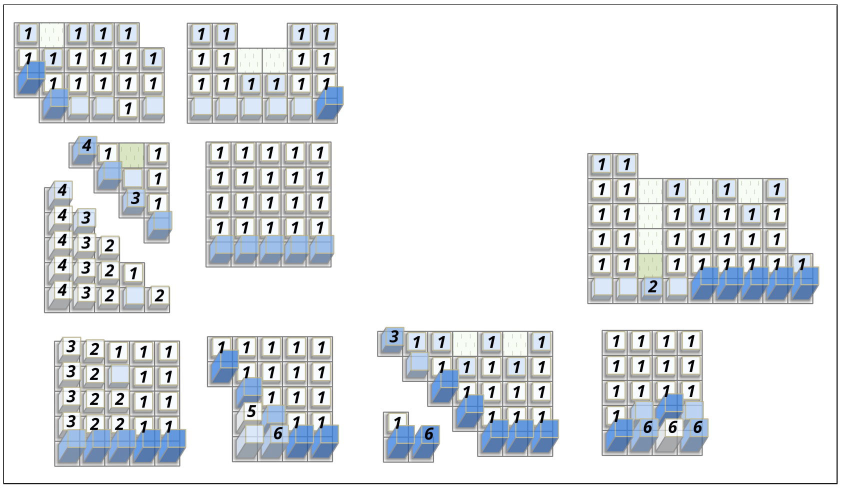
share of parks, respectively. Within the given ranges of FAR and park share, the FAR has a bigger effect on the LVF. This observations will get clear when looking at the maps in figure 7.11.

For a low FAR of 1 and a low park share of 5 % a very high LVF is obtainable: 78 % of all floors have a nice view (figure 7.11b). For most blocks the highest buildings, and thus with best view, are located at the south-eastern-most row of parcels, the furthest away from the next block in the direction of the landmark. This has two implications: the highest buildings line up at the south-eastern border of the plan, perpendicular to the direction of a nice view. Additionally, there is a diagonal line of high buildings. Almost all buildings located north of this diagonal have only one floor. The parks are mainly located at the north-western border of the blocks and unevenly distributed over the neighborhood. This could be counteracted by a constraint on the spatial distribution of parks.

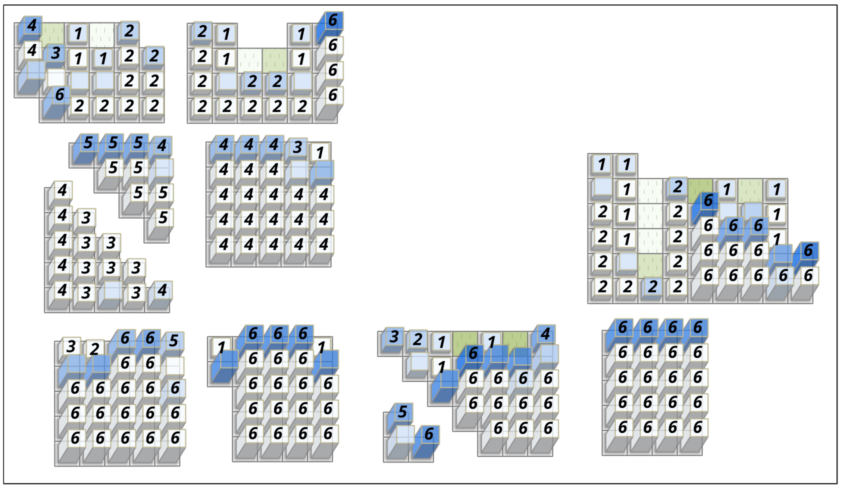
For the same density but a higher share of parks of 20 %, the achievable LVF is 64 % (figure 7.11a). The higher number of parks implies that less parcels can be occupied by buildings. In order to achieve still the same FAR, the floors have to be stacked up to less, but higher buildings. These few, high buildings are obstructing the view more than many, small buildings. The parks are arranged in the form of long “alleys” in the direction of the landmark. More shaded areas are located at the southern-eastern ends, surrounded by the higher buildings with nice views. Due to those alleys, many floors of these buildings, however, have rather a tunnel view on the landmark. An improvement of



(a) Plan 3: FAR 1.0, park share 20 %



(b) Plan 4: FAR 1.0, park share 5 %



(c) Plan 5: FAR 2.0, park share 5 %

Figure 7.11 – Urban form, landmark view, and park irradiation for selected plans of varying densities and park shares (numbers indicate total floors)

the concept of the LVF could thus include the visible range of the landmark. Furthermore, those alleys could be combined to form less numerous but therefore wider park alleys by increasing the perimeter $d_{\text{blg@parks,max}}$, within which the surrounding buildings should be considered, for the constraints on coherence (3.15) and diversity (3.16). Those alleys also bring about that especially from the south-eastern ends of the parks, the landmark is more visible. Thus, in comparison to the previous plan 4, a shift from private view towards public view can be stated.

For the same park share as for plan 4, but with a higher density of 2, at most 39 % of all floors can have a nice view (figure 7.11c). Rather than lines of high buildings, the algorithm generates blocks of mainly the same building height, where height differences mainly occur between blocks. Here, the first row of each block in view direction enjoys a nice view. Parks are located at almost the same parcels as for the case of a lower density.

7.6 Contexts

In the previous sections, several aspects of complexity in urban planning were addressed. A further one concerns the trajectory of systems, which imply that results of planning projects are not necessarily transferable due to the specific context of each project. This aspect is addressed in the following by applying the developed computational framework to a new development project in Asia (section 7.6.2) and to a redevelopment project in Switzerland (section 7.6.1).

7.6.1 From Europe to Asia

This case study is presented in section 6.3. The context of a new development in the center of one of the larger Asian cities, whose space is additionally limited by the sea, implies much higher expectations in terms of density. However, with sustainability being a global concern, this should be achieved in a sustainable way. This sustainability concerns not only the share of RES employed for the energy supply but also the energy autonomy of the new district. The PV shift will be used as criteria for the latter. It designates the share of electricity from PV panels that, due to a lack of simultaneous demand, has to be shifted to hours, during which the demand exceeds the production of electricity. Hence two questions will be addressed for this case study in the following sections.

Densification potential

The first one deals with the quantification of the potentially conflicting goals of maximizing the density and the share of RES. This is reflected by the following optimization problem:

$$\begin{aligned} \max \quad & \boldsymbol{FAR} \\ \text{subject to} \quad & s_{\text{res,min}} \leq \boldsymbol{s_{\text{res}}} \end{aligned} \tag{7.7}$$

The solutions to this problem in figure 7.12 show that there is indeed a trade-off between both targets: The maximum achievable FAR decreases from 11.6 to 2.9 as the minimum share of RES increases from 20 % to 70 %. These maximum densities are achieved for purely residential use, since their total demand is the lowest.

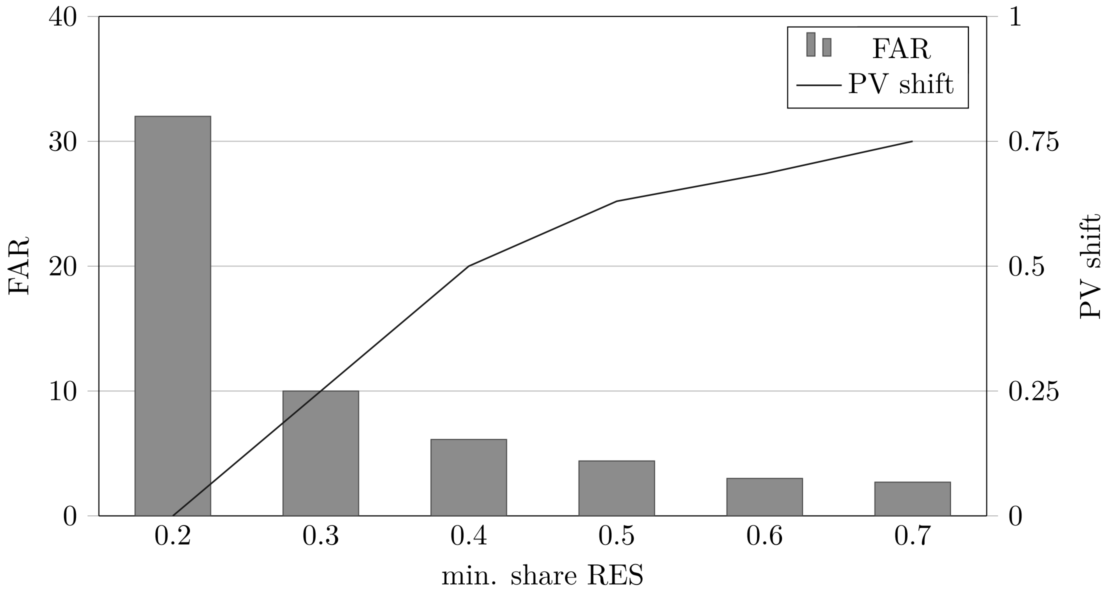


Figure 7.12 – Maximum achievable densities (bars) and the share of shifted electricity from PV (line) with respect to minimum shares of RES

With an increasing share of RES, an increasing amount of electricity has to be supplied by locally installed PV panels. However, a high percentage of electricity generated from PV has to be shifted to other hours, as the demand profiles of residential use (figure 6.5 do not coincide so well with the profile of solar potential availability.

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Energy autonomy

A second question is, whether the shift of electricity from PV can be reduced while still increasing the density and the share of RES. The formulated optimization problem comprises the maximization of the difference between electricity production from PV and the surplus electricity (which would have to be exported or stored), accumulated over all time steps:

$$\begin{aligned} \max \quad & \sum_t \left(\sum_{pc} \boldsymbol{E}^{pc,\text{pv},t} - \boldsymbol{E}^t_{\text{exp}} \right) \\ \text{subject to} \quad & FAR_{\text{min}} \leq \boldsymbol{FAR} \\ & s_{\text{res,min}} \leq \boldsymbol{s}_{\textbf{res}} \end{aligned} \tag{7.8}$$

A comparison of the results of the two optimization problems displayed in figures 7.12 and 7.13, respectively, reveals that the PV shift can be indeed reduced by foreseeing a greater mix of occupancy types. It shall be hinted that in case no PV shift appears, the objective function is at its lower bound. Hence it is not deducible that the identified mixture of occupancy types is the unique solution that minimizes the objective while respecting the given constraints.

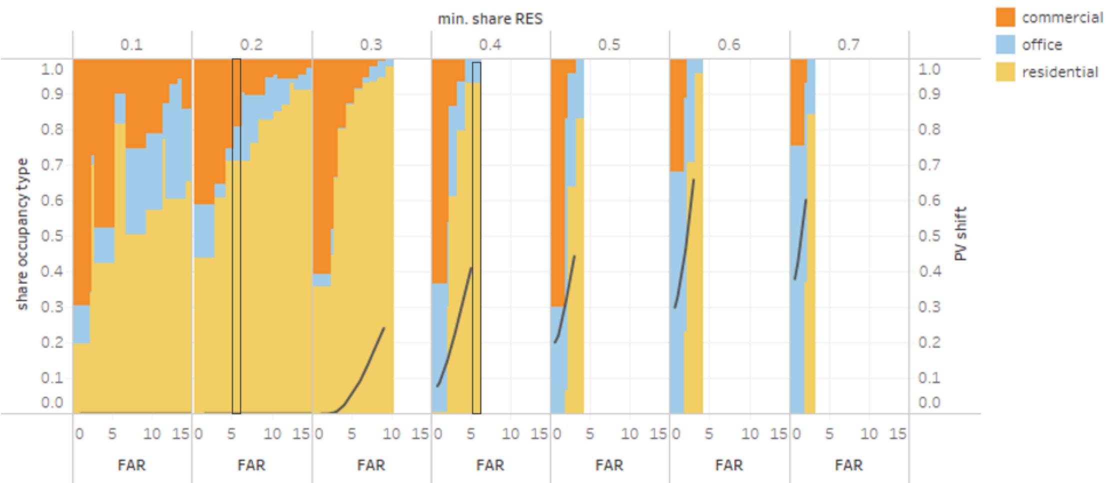

Figure 7.13 – Occupancy types and PV shift in dependence on minimum share of RES and minimum FAR (outlined scenarios presented in figure 7.14)

Figure 7.14 displays the electricity supplied to different technologies to satisfy the useful energy demand and the surplus electricity, which results from PV and is not instantly required to satisfy local demands and thus needs to be shifted.

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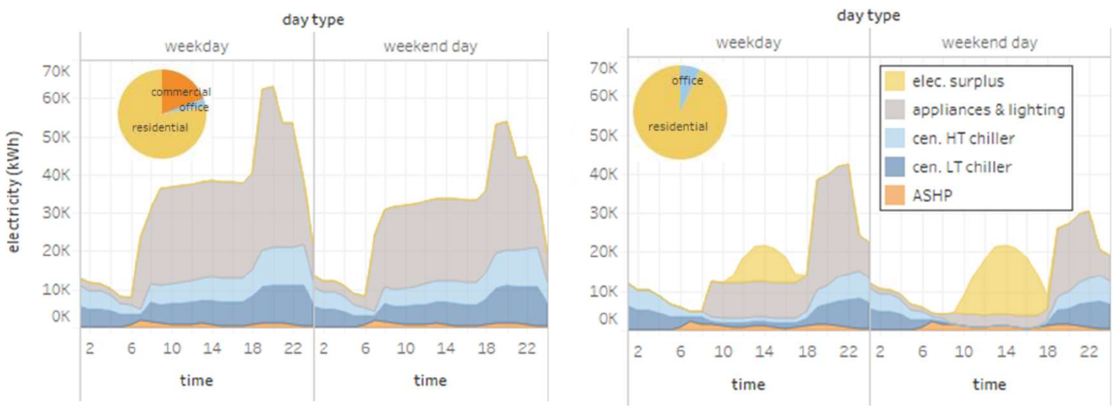


(a) Minimum share of RES: 20 %

(b) Minimum share of RES: 40 %

Figure 7.14 – Hourly profiles of electricity supplied to different conversion technologies and surplus electricity produced from PV that needs to be shifted

7.6.2 From new developments to redevelopments

The second change of context concerns the shift from the development of a new neighborhood to the redevelopment of already urbanized land. The according case study is presented in section 6.2. All optimization problems stated in this section were solved to a MIP gap of 1 %.

Current energy system

In order to evaluate future improvements to the energy system, it is required to establish reference values, namely (i) the current demand by building and end use, (ii) the type and size of existing conversion systems, (iii) the according energy carrier imports, (iv) and the corresponding GHG emissions. While the norms (section 6.4.3), the available measured annual demands (section 6.2) and the statistical demand model (chapter 4) allow to estimate the demands of almost all considered buildings, information about existing energy conversion systems is available for only about 40 % of the buildings (section 6.2). Therefore, additional assumptions must be made. Here, it is assumed that the shares of known existing energy conversion systems reflect the current state in the entire planning zone and that these unknown energy conversion systems are distributed in order to minimize overall investment costs:

$$\min \sum_{pc,et,cb} af^{cb,et} \cdot \boldsymbol{C}_{\mathbf{inv}}^{cb,pc,et} \tag{7.9}$$

Consequently, the option of a connection to a district heating network is excluded, since this network is not yet in place. The minimization of the investment costs for energy systems leads to the type and size of systems shown in figure 7.15. Figure 7.16 (blue line) and table 7.1 show the values of key criteria for the reference scenario. It is pointed

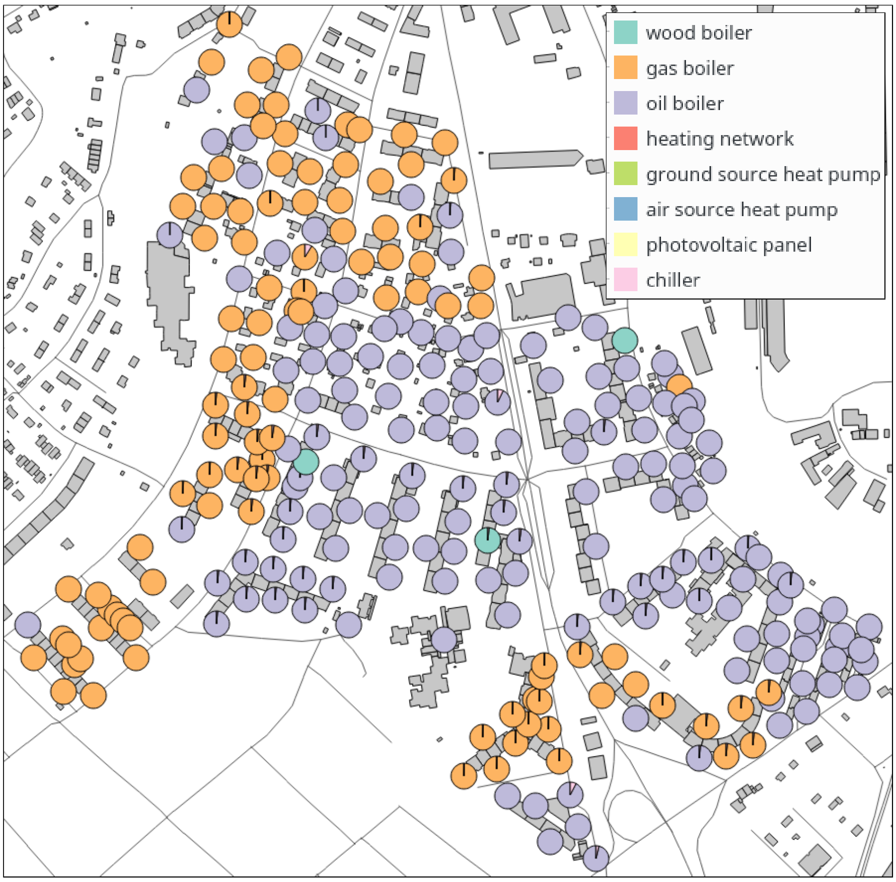


Figure 7.15 – Annual energy supply by conversion system estimated by applying the shares of known energy conversion systems to the entire planning perimeter and assuming that the cheapest system in terms of investment costs is in place

out that the investment costs are not equal to zero, as energy conversion systems have to be “installed” where information on existing systems is not available.

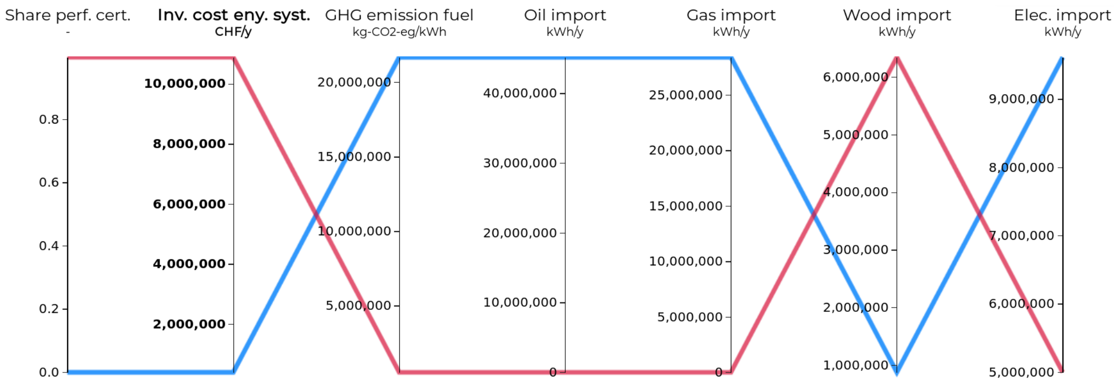


Figure 7.16 – Key criteria for the reference scenario (blue) and the scenario with minimum GHG emissions (red)

Table 7.1 – Numerical results for the reference scenario and the scenario with minimum GHG emissions

criteria	unit	reference	min. emissions
investment costs	MCHF/y	0.393	10.89
GHG emissions	t-CO2-eq/kWh	21 680	538.34
share RES	%	7	89
oil import	GWh/y	45.19	0
natural gas import	GWh/y	28.42	0
wood import	GWh/y	0.873	6.35
electricity import	GWh/y	9.62	5.00
room heating demand	GWh/y	64.7	5.48
room cooling demand	MWh/y	332.9	1 020
electricity demand	GWh/y	9.13	9.13
refurbishment rate	%	0	99.6

Densification potential

Starting from the current state of existing buildings, the maximum density is determined by the following optimization problem:

$$\max \quad \boldsymbol{FAR} \tag{7.10}$$

Since no new constructions are foreseen, the density can only be increased by building additional floors on top of existing buildings. However, these elevations are limited by overall and building type-specific maximum height constraints and if buildings are listed. The thus identified potential for densification is about 8 % (figure 7.17). Note that, although the existing buildings in “Les Palettes” comprise in average more floors than the new buildings in "Les Cherpines", the range of density is considerably lower (compare section 7.1 f.). The reason are the relatively larger parcels in "Les Palettes", which are used to determine the reference area for the FAR.

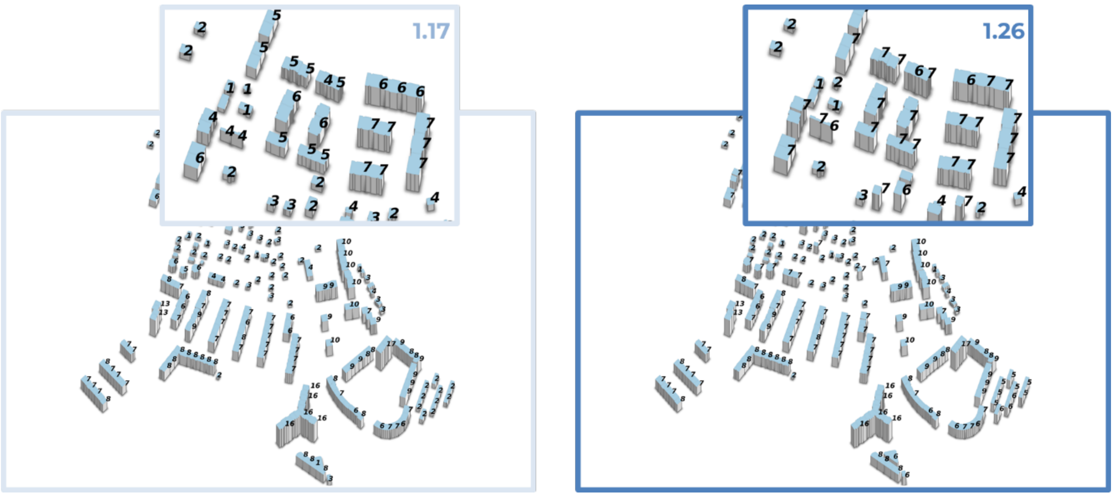


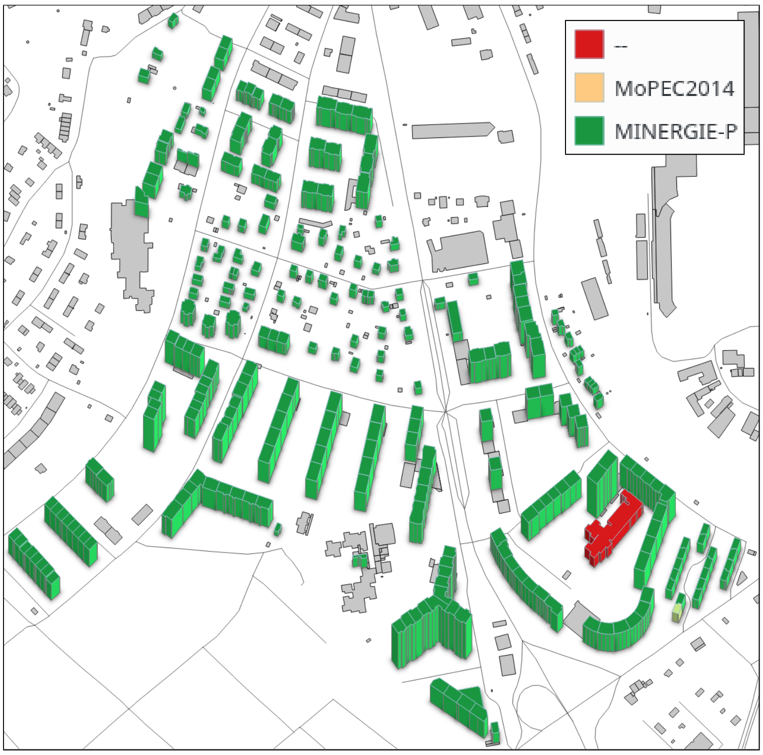
Figure 7.17 – Number of floors of buildings and the according FAR: maximizing the latter leads from the current state (left) to the maximum density without constructing new buildings and while respecting permissible building heights (right). The enlarged maps illustrate buildings which would have to be extended.

Reduction of GHG emissions

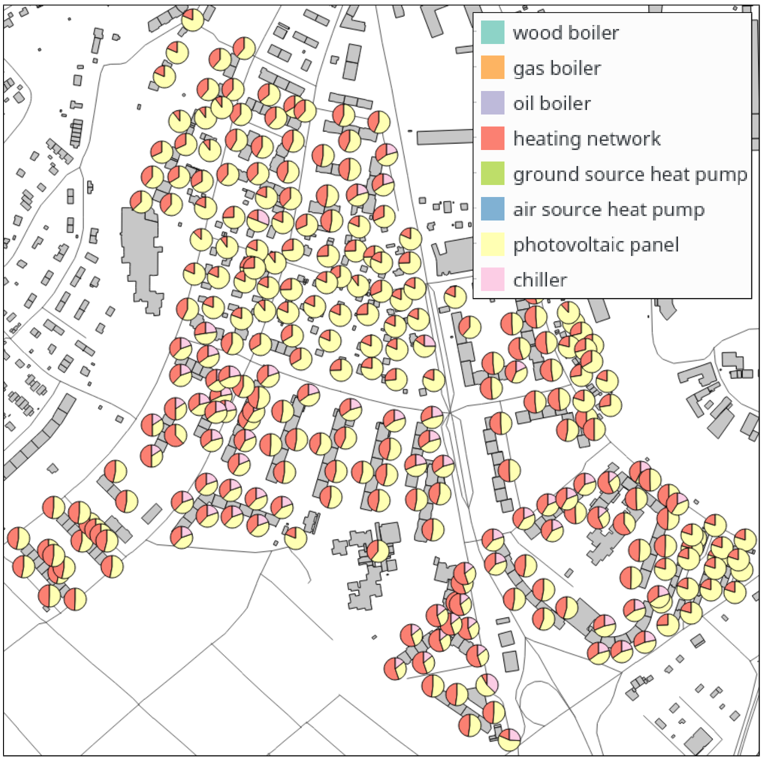
Proceeding from the reference scenario (see page 118), the maximum achievable reduction of GHG emissions is determined by minimizing the latter:

$$\min \quad \boldsymbol{Em}_{\mathbf{ghg}} \tag{7.11}$$

The results are depicted in table 7.1 and figure 7.16 (red line). To achieve such low emissions, it is necessary to renovate all buildings that are not listed, according to the strictest considered energy standard (figure 7.18a). In addition, all buildings are equipped with photovoltaic panels and connected to the district heating network (figure 7.18b). It can be seen that the annual energy output by conversion systems installed in SFHs in the center and the south-east, respectively, of the planning perimeter, is dominated by electricity from PV panels. The reason for this is that smaller buildings have a larger roof surface in relation to their overall energy demands. This electricity is either consumed within those buildings or exported to the local electric grid.



(a) Selected energy standard: all buildings that are not listed, are refurbished according to the standard Minergie-P.



(b) Annual energy supply of installed conversion systems: all buildings are mainly supplied by the heating network and photovoltaic panels

Figure 7.18 – Maps for the minimization of GHG emissions

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Cost-effective increase of the share of RES

While it is indeed highly desirable to minimize GHG emissions, it is still important to consider the costs implied. Thus, in a further iteration, solutions are sought that are both environmentally and economically sustainable. To achieve this, the total energy system costs are minimized while the minimum permissible share of energy from RES is systematically varied (figure 7.19).

$$\begin{aligned} \min \quad & \sum_{pc}\sum_{et}\sum_{cb}\left(af^{cb,et}\cdot \boldsymbol{C}_{\mathbf{inv}}^{cb,pc,et} + \boldsymbol{C}_{\mathbf{op}}^{cb,pc,et}\right) \\ \text{subject to} \quad & s_{\text{res,min}} \leq \boldsymbol{s}_{\mathbf{res}} \end{aligned} \tag{7.12}$$

This approach allows to generate Pareto-optimal solutions regarding the two considered objectives.

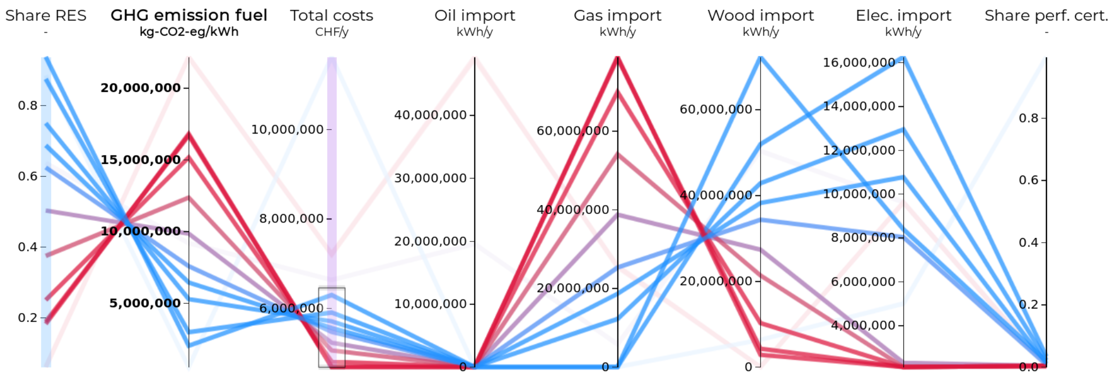


Figure 7.19 – Cost-effective increase of the share of RES (purple axis: optimized criteria, blue axis: varied criteria)

First, it can be noted that reducing costs is indeed in conflict with increasing energy from RES. This is indicated by the colored lines which are ordered synchronously on the axes of "share RES" and "total costs". Besides, an increase in the share of RES results in a progressive decrease of natural gas imports and an increase of wood and electricity imports. The latter is used to drive heat pumps as the electricity demand for end uses remains constant, if buildings are neither refurbished nor enlarged, i.e., the density remains constant. Since the total costs were minimized, they are indeed much lower than those for a single-objective minimization of GHG emissions.

A look at the refurbishment rate ("share performance certificates") reveals that a thermal refurbishment of building envelopes does not constitute the most cost-effective way to reduce emissions or increase the share of RES. However, currently only complete refurbishments of buildings are considered. A future improvement of the model and results would be to differentiate between the various measures (e.g., roof, facades, glazing), which could lead to the identification of the most cost and energy efficient measures.

Refurbishment

While the above results indicate that complete refurbishment is not necessarily the most competitive measure, higher refurbishment rates might nevertheless be desirable (i) as the reduction of energy demand should be preferred to an increase of system efficiency, or (ii) for political reasons, like the availability of dedicated cantonal or national funds. In this direction, the task would rather be to determine the ideal allocation of financial resources to achieve the highest energy savings. This question can be answered by minimizing refurbishment costs while varying the maximum permissible heating demand (figure 7.20).

$$\begin{aligned} \min \quad & \sum_{pc} af_{\mathrm{rfb}} \cdot \boldsymbol{C}^{pc}_{\mathbf{rfb}} \\ \text{subject to} \quad & E_{\mathrm{rh,min}} \leq \sum_{pc} \boldsymbol{E}^{pc}_{\mathbf{rh}} \end{aligned} \tag{7.13}$$

The results show that, in general, large buildings are more attractive than small ones (figure 7.21a) and which single buildings are the most effective to be refurbished (figure 7.21b). Furthermore, from the parallel coordinate plot (figure 7.20) it can be seen that the costs do not increase proportionally to the refurbishment rate: for low rates the costs increase superlinearly, for high rates they increase sublinearly. This is another indicator that large buildings get refurbished before small buildings.

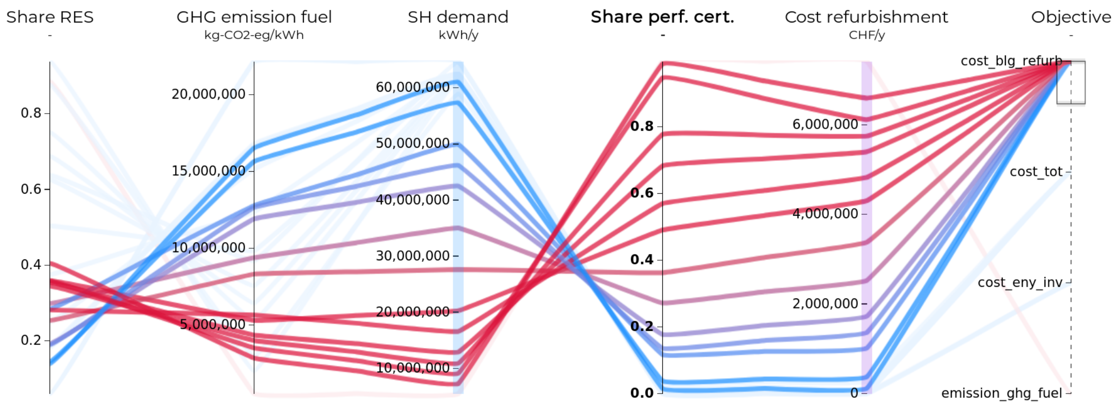
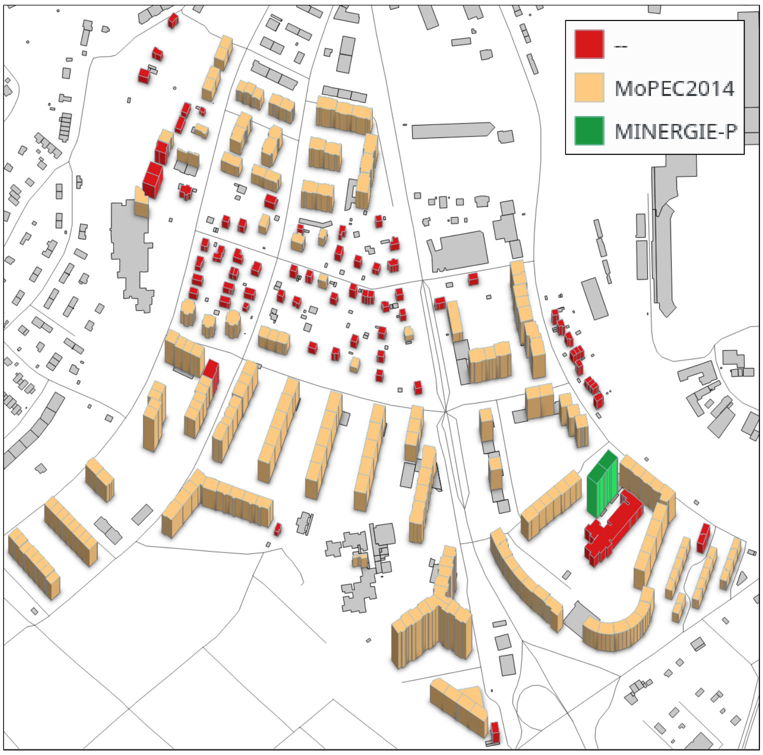


Figure 7.20 – Parallel coordinate plot of scenarios generated by a minimization of refurbishment costs while systematically varying the permissible heat demand (purple axis: optimized criteria, blue axis: varied criteria).

7.7 Ranges

A last addressed aspect of complexity, as introduced in section 1.2, concerns setting the range that is to be considered for a planning project.



(a) High refurbishment rate (78 %): large buildings are more attractive to refurbish than small ones.

(b) Low refurbishment rate (27 %): identification of the most attractive buildings to refurbish.

Figure 7.21 – Selected energy standards for an optimal allocation of financial resources

7

As this section will show, the chosen range can indeed impact the outcomes of the analysis and consequently the planning decisions. This issue is demonstrated by repeating the analyses carried out in the previous section for the development project “Les Palettes”, but this time varying the spatial range considered. This means that the stated optimization problems are solved separately for the three neighborhoods, which constitute the overall planning project: “Les Palettes”, “Le Bachet”, and “Les Semailles” (section 6.2). All optimization problems stated in this section were solved to a MIP gap of 1 %.

7.7.1 Current energy system

First the current energy systems of the three neighborhoods are assessed. As previously, in order to get an estimation where information about existing systems is missing, the shares of known systems within one neighborhood are assumed to hold for the entire neighborhood. These shares are quite different between the three neighborhoods as detectable via the numbers of different boilers shown in figure 7.22a. The buildings in “Les Palettes” and “Le Bachet” are mainly equipped with oil boilers, while the buildings in “Les Semailles” are mainly equipped with natural gas boilers. In combination with higher gross floor areas, this should lead to higher emission saving potentials in the first two neighborhoods.

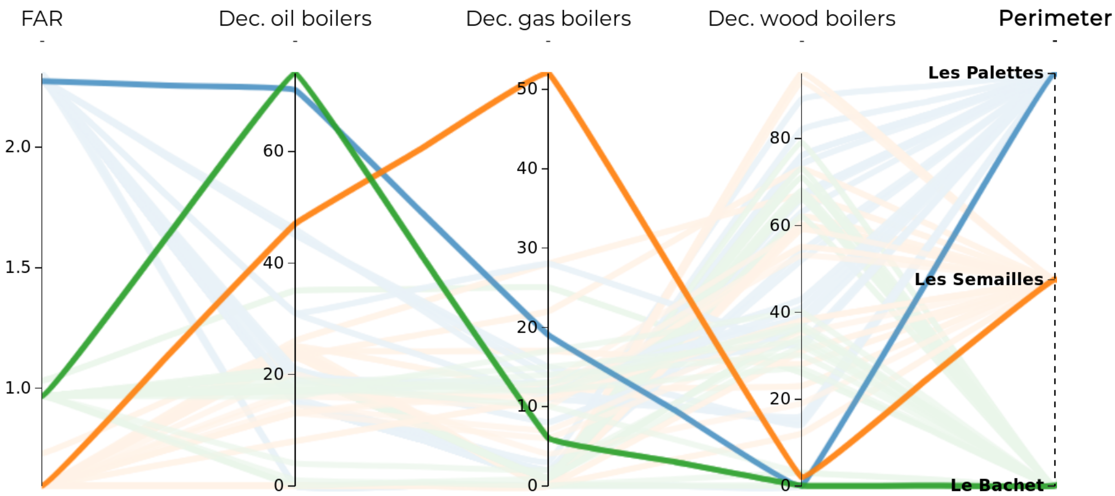
Figure 7.22b shows that the energy imports are in accordance with the number of boilers with two exceptions: (i) The gas imports to “Les Palettes” are almost as high as to “Les Semailles” and (ii) the oil imports to “Les Palettes” are a bit higher than to “Les Bachet” although there are less oil boilers installed in “Les Palettes”. From this it is obtainable that generally the largest boilers are installed in “Les Palettes”. Thus if fossil fuel boilers were to be replaced in order to reduce the environmental impact, the highest effect with the least replacements could be obtained by focusing on “Les Palettes”.

The structure of the energy supply system for each neighborhood gets plausible when regarding the according distributions of occupancy types (figure 7.22c). While all neighborhoods are mainly residential, “Les Bachet” comprises the most educational functions and “Les Palettes” the most commercial functions. In combination with an overall low density one can conclude that “Les Semailles” consists mainly of SFHs.

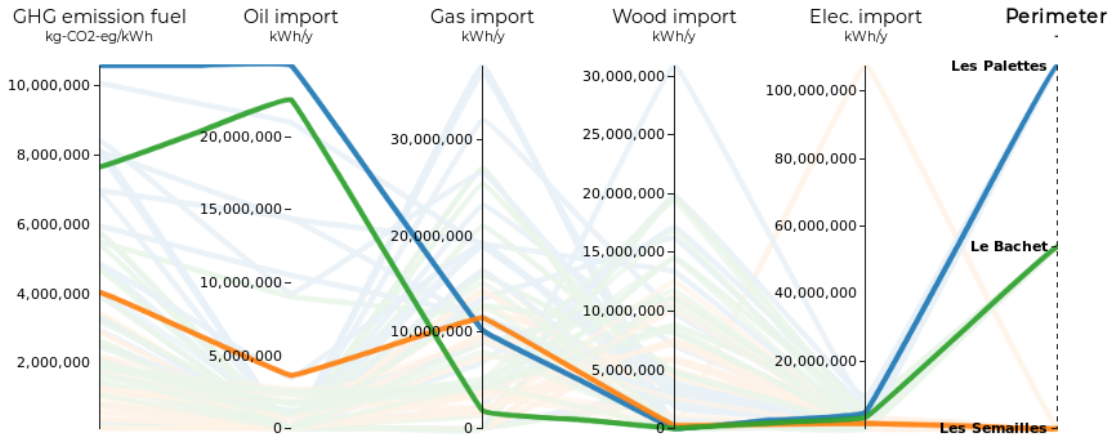
7.7.2 Densification potential

The densification potentials for the three neighborhoods are displayed in figure 7.23. It shows that it is the highest both in absolute and relative terms for “Les Semailles”, followed by “Le Bachet”, and almost negligible for “Les Palettes”.

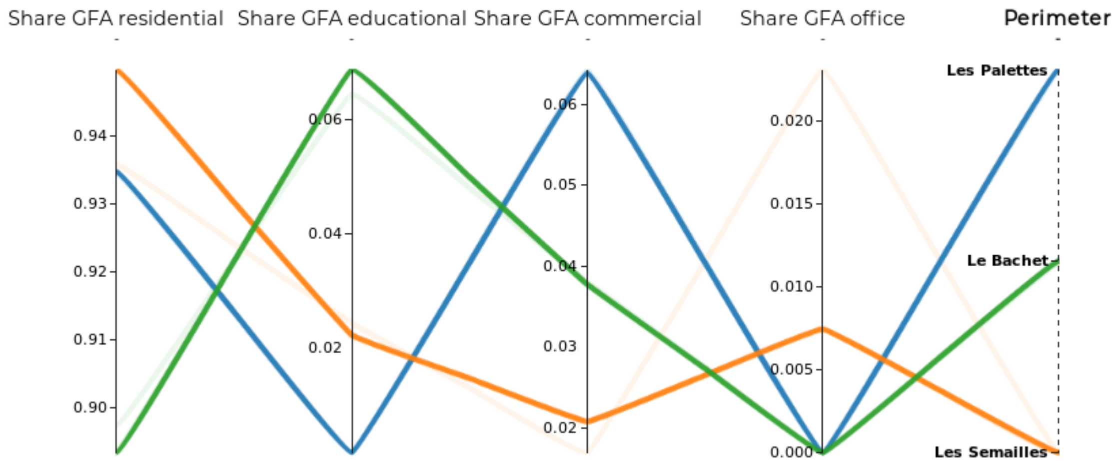
All in all, these potentials are not very high for two reasons: (i) Only the construction of new floors on top of existing buildings and not the construction of new buildings is



(a) Density and number of boilers



(b) Energy imports



(c) Shares of occupancy types

Figure 7.22 – Key criteria for the current state of the three neighborhoods of the planning project “Les Palettes”

7

considered for the densification. This implies also that the building area ration (BAR) remains unchanged. (ii) A building type-specific maximum building height is respected in order to avoid SFHs with, for example, a footprint area of 50 m^2 but 7 floors. Nevertheless, the potential is the highest for "Les Semailles" with the most SFHs.

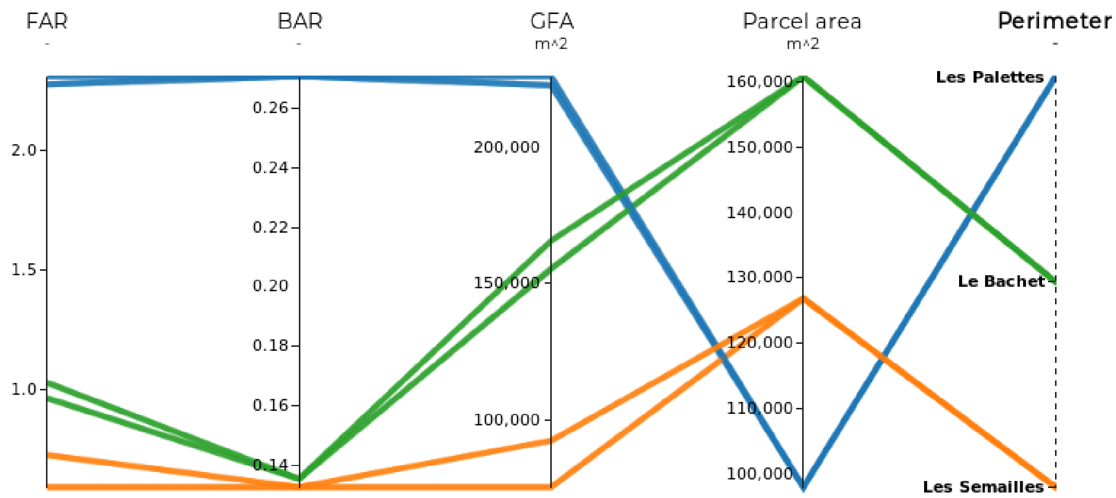


Figure 7.23 – Maximum densification potential and further density-related criteria

7.7.3 Reduction of GHG emissions

Figure 7.24 shows the GHG emission saving potentials. As anticipated in section 7.6.2, "Les Palettes" offers indeed the highest savings.

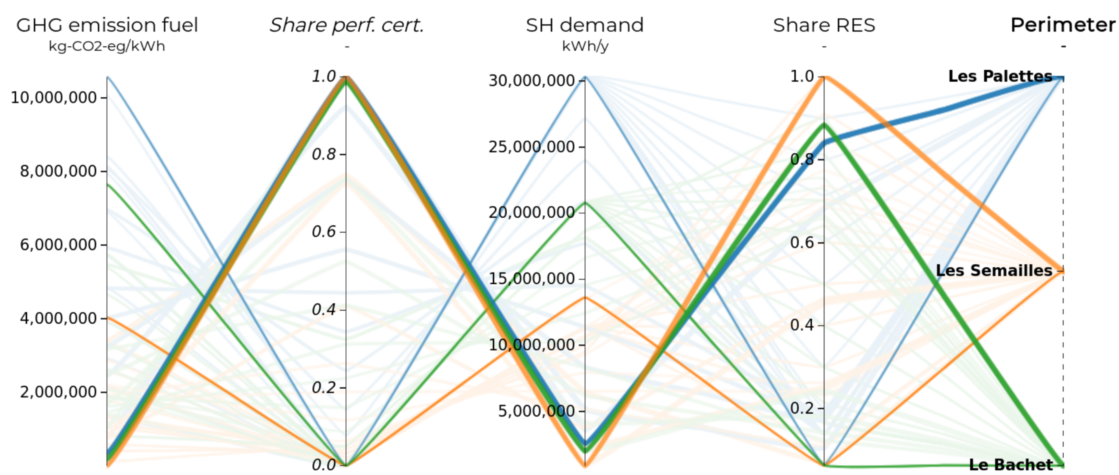
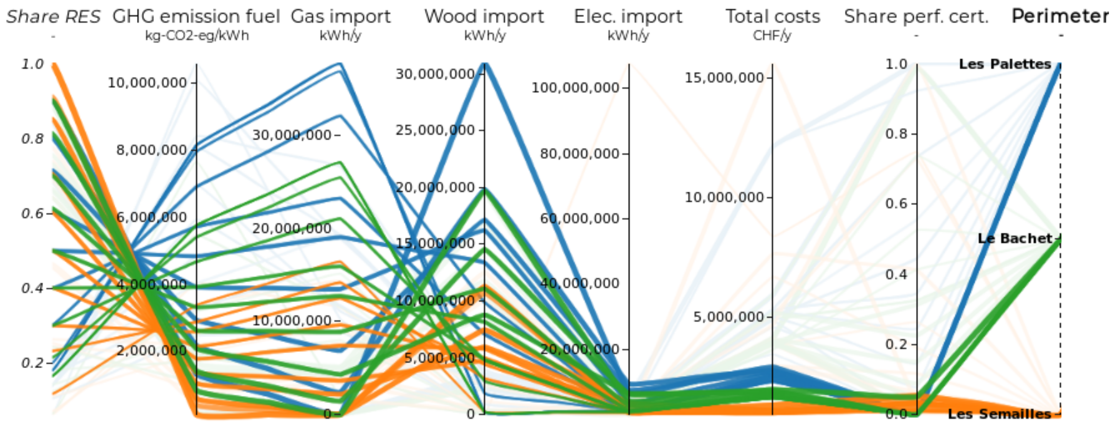


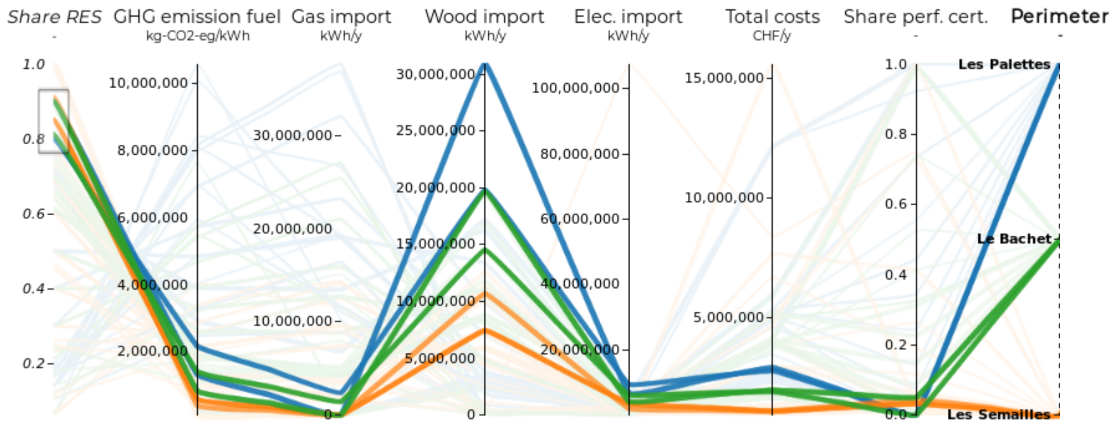
Figure 7.24 – GHG emission saving potentials by neighborhood (thin lines indicate the emissions associated to the current energy system and thick lines indicate the minimum possible emissions)

7.7.4 Cost-effective increase of share of RES

Figure 7.25 shows the results of solving the optimization problem (7.12) for each neighborhood.



(a) Overview of solutions



(b) Focus on solutions for shares of RES of 80 and 90 %

Figure 7.25 – Cost-effective increase of share of RES per neighborhood (line thickness increasing with share of RES)

A share of RES of 100 % is only feasible for "Les Semailles". The reason being that smaller buildings have a larger roof surface available for PV panels in relation to their demands (see section 7.6.2, figure 7.18b).

It is further remarkable that in order to increase the share of RES from 80 to 90 % (figure 7.25b) for "Les Palettes", the wood imports have to be increased by 50 %. The other two neighborhoods are less dependent on wood as their respective imports increase by about 33 % each. For those two neighborhoods, high shares are achieved partly due to the refurbishment of some buildings.

7.7.5 Refurbishment

Figure 7.26 shows the solutions of the optimization problem (7.13) for the individual neighborhoods. Maps of the three solutions with a refurbishment rate of about 73 % are displayed in figure 7.27.

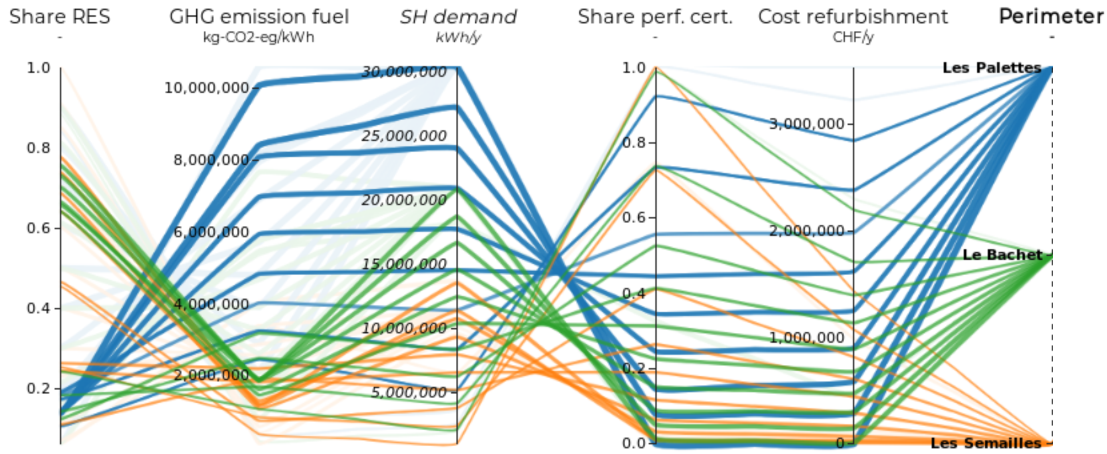


Figure 7.26 – Cost-effective refurbishment by neighborhood (line thickness increasing with space heating (SH) demand)

In comparison with the results obtained when solving the optimization problem for all three neighborhoods together (figure 7.21), it is notable that in Semailles some SFHs are also refurbished while in the other two neighborhoods some additional, predominantly small buildings are not selected for refurbishment anymore.

Taking a step back allows to draw the following conclusions: for some of the optimization problems (7.9) to (7.13), a variation of the considered range did not lead to different results. The results obtained for all neighborhoods are a sum of the respective results obtained for each individual neighborhood. This holds for the maximization of the density and for the minimization of GHG emissions, as the optimization problem only consisted in a linear objective function without the specification of any constraints. For slightly more complicated problems, however, this observation is no longer true. The results for a cost-effective increase in the share of RES (section 7.7.4) and refurbishment (section 7.7.5) differ when considering the three neighborhoods either separately or all together.

Most of the time considering a larger spatial range can reveal synergies between different neighborhoods, as observed for the question for a cost-effective refurbishment: only the consideration of the three neighborhoods together revealed that it is indeed better to direct more funds to “Les Palettes” and “Le Bachet” and less to “Les Semailles”.

Figure 7.27 – Selected energy standards for an optimal allocation of financial resources per neighborhood at a refurbishment rate of about 73 %

Sometimes, however, limiting the considered range is also beneficial, as for the insight that for “Les Semailles” a share of RES of 100 % is feasible. This was not observable when considering all three neighborhoods together.

Conclusion

Contributions

The core contributions of this thesis are recapitulated from page 8:

1. the elaboration of computational methods to generate and handle a large number of alternatives
2. the integration of many different aspects of cities and urban planning in one optimization model and
3. the demonstration of the capabilities of the developed planning support system to address identified aspects characterizing cities and urban planning.

In the following, contributions to each field are listed.

Urban planning and energy

This work is contributing to the integration of energy into urban planning by the combination of optimization models from both fields.

Urban complexity

The performed systematic assessment of urban complexity and the subsequent proposition of computational methods to address a great number of aspects might inspire to follow a similar approach to the development of new tools for this or other fields dealing with complex systems.

Optimization method

This is respected by adopting a computational method that is highly versatile and thereby facilitating interactive optimization: multi-parametric programming. It is thus possible to declare objective functions and/or constraints for a great number of performance indicators and vary many input parameters. Despite the fact that it is well suited, multi-parametric programming was so far not applied to urban planning problems.

Optimization model

The integration of a great number of domains and scales into one model allows to simultaneously regard multiple aspects of urban planning, which commonly have to be tackled with different tools.

Optimization model formulations

Novel MILP formulations are proposed for

- new and existing buildings, including their energy standard,
- the quantitative assessment of the view on a landmark,
- the assessment of solar potential via cumulative skies,
- parks and their close surroundings.

Data model

The large number of potential scenarios of an urban planning project requires to manage both the data related to the generation of scenarios and the context-specific data describing the city. This is addressed by the development of a new data model for interactive optimization and the coupling with a semantic 3D city model.

Obtainable outcomes

The resulting computational system is demonstrated based on three case studies. A first set of questions addresses the relations between the building density, the sustainability of the energy supply, the distribution of buildings, and the costs of different actors and on different scales. A sensitivity analysis identifies the impact of changing wood pellet prices. The results reveal tipping points regarding the preference for a decentralized or centralized energy supply system. Changing from energy to social aspects, relations between the building density, the feasible share of parks, and the view on a landmark are quantified.

Changing the context from Europe to Asia implies different boundary conditions in form of higher target densities and different climatic conditions. The addressed questions revealed the maximum achievable densities in function of sustainability and the mix of building functions that benefits energy autonomy most. A change from the development of a new neighborhood to the development of an existing neighborhood results in an increased number of spatial constraints and different questions. Targeting a cost-effective increase of the building refurbishment rate, results show both which types of buildings and which individual buildings should be refurbished first. A last set of questions considers the influence of the considered range on the outcomes: increasing the range can reveal synergies leading to globally better solutions. The example demonstrates that by directing refurbishment subsidies to specific neighborhoods more energy savings can be achieved for less investments.

Limitations

Validity of results

Model-based methods face the trade-off between detail and accuracy on the one hand and computational costs on the other hand. The one proposed lies between these poles: It is more detailed but also more costly than spreadsheet tools, which serve to do rough estimations, but are limited when it comes to generating and optimizing a great number of plans. On the other hand it is less detailed but also less costly than dynamic simulation tools, which serve to e.g. create operation schedules, and which are mostly fit for specific purposes, such as the estimation of energy demand in buildings or transport needs. These kind of tools would further have to be coupled with heuristic optimization methods to reveal similar insights as the proposed tool is able to give.

The advantage in computational speed over the group of simulation tools is partly achieved by only allowing linear model formulations. They come at the price of reduced model accuracy since many phenomena arising in the urban context are of non-linear nature. Although this can be partly overcome by piecewise linearization of non-linear functions, as also employed in this work, this remains an approximation. However, since the task in early-phase urban planning is to create, compare and decide between different sketches, users might be ready to accept a lower degree of accuracy for getting a better overview of their decision space in a faster way. A certain number of thus identified sketches could then be validated with more accurate and detailed simulation tools.

Interpretability of results for greenfield planning

Another limitation next to the accuracy of all results, is the interpretability of the generated results for greenfield planning. On the one hand plans found by numerical optimization should first of all be considered as extreme solutions (Keirstead and Shah, 2013, p. 330 f.). Although there is the possibility to make the plans less extreme and more balanced by subsequently adding constraints respecting more and more aspects, their extreme nature will persist. It is therefore left to the planner to adequately make use of these extreme solutions and insights in a meaningful way (deVries et al., 2005).

On the other hand, interpreting the generated abstract urban form, depicted by a regular grid occupied with cubes, is not straightforward. This form should be interpreted as representing relationships (Bruno et al., 2011, p. 105) and would naturally not be built directly. So far the planner would still have to deduce the rules expressed by the arrangements of the blocks and translate them into a realistic urban form. A first step in such a process could be to move the buildings as placed by the algorithm within their parcels or to reshape their footprint while respecting the floor area ratio, building height and floor types as calculated by the model. However, the greater these changes, the more likely it is that certain calculated indicators do not hold anymore. Thus a validation with more detailed simulation tools would become even more important. One could also think of a new series of optimizations using different assumptions on size and position of footprints and parcels. In summary the generated results, not only but especially concerning the urban form, should not be seen as dogmatic but indicative.

Balanced modeling

A third limitation lies in the fact that not all aspects of urban systems are easy to quantify and thus to include in the model (Ligmann-Zielinska et al., 2008; Bruno et al., 2011). Williams, (2013) states that the necessity to take decisions, however, often implies an implicit quantification of “unquantifiable concepts”, and that in comparison to such an implicit quantification, the endeavor to make a quantification explicit is preferable. The degree of ease with which criteria can be measured and modeled can even affect the attention they are given (Roy, 1985; Meadows, 1998; Desthieux, 2005). In this line it would be imperative to include as many aspects as possible in the model, even though or yet especially if they seem very hard to quantify. Another approach would be to use the proposed computational framework to identify a few plans that are promising concerning the modeled aspects and subsequently assess these plans regarding aspects that are not modeled. The arrangement of buildings for example illustrates well both philosophies: design rules based on expert knowledge could possibly be identified, which could then be implemented in the model. On the other hand, the generated maps allow – with a certain faculty of abstraction – an a-posteriori judgment by a human (Bruno et al., 2011, p. 106).

Outlook

In the following some potential directions for future work and outlooks, regarding expectable and desirable developements in the field, are highlighted.

Domains

Much more aspects of urban systems could be considered. The current model incorporates for example only direct energy demand and corresponding greenhouse gas emissions associated to the operation of the energy system. Future work could thus concern the implemention of the embodied energy and emissions due to the construction of buildings and the energy supply system. The underlying trade-offs between embodied and operational energy should indeed influence the decisions (Kellenberger et al., 2012, p. 86). The primary energy demand for energy technologies would also allow to compare the performance of the neighborhood with target values as defined by the 2000-Watt society concept (Schweizerischer Ingenieur- und Architektenverein, 2011). Likewise non-energy related environmental aspects could be included as e.g. soil permeability. A domain which was so far entirely left aside concerns the mobility aspects.

Actors

More actors could be considered and actors currently regarded as a homogeneous group could be separated into subgroups or even individually considered. For example, a separation of the group of owner-occupants could allow to address issues related to the landlord-tenant dilemma. The consideration of individual actors could imply the definition of constraints that hold for specific buildings only.

Scales

The consideration of larger time scales would allow to determine not only where and what kind of buildings or equipment shall be built or purchased, respectively, but also at which point in the future. Potential approaches to this are multi-period optimization or rolling horizons.

Phases

The construction and demolition of buildings could be considered by associated costs and life-cycle analyses.

Information

The adoption of data standards in cities would facilitate the use of computer tools like URB^{io}.

Bibliography

Adami, Christoph, Charles Ofria, and Travis C. Collier (2000). “Evolution of Biological Complexity”. In: *Proceedings of the National Academy of Sciences* 97.9, pp. 4463–4468. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.97.9.4463. pmid: 10781045. URL: http://www.pnas.org/content/97/9/4463.

Aebischer, Bernard, Giacomo Catenazzi, and Martin Jakob (2007). “Impact of Climate Change on Thermal Comfort, Heating and Cooling Energy Demand in Europe”. In: *Proceedings Eceee*, pp. 23–26.

Aelker, Judith, Thomas Bauernhansl, and Hans Ehm (2013). “Managing Complexity in Supply Chains: A Discussion of Current Approaches on the Example of the Semiconductor Industry”. In: *Procedia CIRP*. Forty Sixth CIRP Conference on Manufacturing Systems 2013 7, pp. 79–84. ISSN: 2212-8271. DOI: 10.1016/j.procir.2013.05.014. URL: http://www.sciencedirect.com/science/article/pii/S2212827113002217.

Agugiaro, Giorgio (2017). *3D City Database Extension for the CityGML Scenario ADE 0.2 PostgreSQL Version Documentation*. URL: https://github.com/gioagu/3dcitydb_ade/blob/master/02_energy_ade/manual.

Agugiaro, Giorgio and Patrick Holcik (2017). *3D City Database Extension for the CityGML Energy ADE 0.8 PostgreSQL Version*. URL: https://github.com/gioagu/3dcitydb_ade/blob/master/02_energy_ade/manual/3DCityDB_Energy_ADE_0.8_Documentation.pdf.

Aksoezen, Mehmet, Magdalena Daniel, Uta Hassler, and Niklaus Kohler (2015). “Building Age as an Indicator for Energy Consumption”. In: *Energy and Buildings* 87, pp. 74–86. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2014.10.074. URL: http://www.sciencedirect.com/science/article/pii/S0378778814009207.

Allegrini, Jonas, Kristina Orehounig, Georgios Mavromatidis, Florian Ruesch, Viktor Dorer, and Ralph Evins (2015). “A Review of Modelling Approaches and Tools for the Simulation of District-Scale Energy Systems”. In: *Renewable and Sustainable Energy Reviews* 52, pp. 1391–1404. ISSN: 13640321. DOI: 10.1016/j.rser.2015.07.123. URL: http://linkinghub.elsevier.com/retrieve/pii/S1364032115007704.

Allen, Peter M. (2012). “Cities: The Visible Expression of Co-Evolving Complexity”. In: *Complexity Theories of Cities Have Come of Age*. Springer, Berlin, Heidelberg, pp. 67–

89. ISBN: 978-3-642-24543-5 978-3-642-24544-2. DOI: 10.1007/978-3-642-24544-2_5. URL: https://link.springer.com/chapter/10.1007/978-3-642-24544-2_5.

Alves, Sonia, Laura Estévez-Mauriz, Francesco Aletta, Gemma M. Echevarria-Sanchez, and Virginia Puyana Romero (2015). “Towards the Integration of Urban Sound Planning in Urban Development Processes: The Study of Four Test Sites within the SONORUS Project”. In: *Noise Mapping* 2.1.

Aristotle (4th century BCE). *Metaphysics*. 8 - 10.

Baccarini, David (1996). “The Concept of Project Complexity—a Review”. In: *International journal of project management* 14.4, pp. 201–204.

Balling, Richard J., John T. Taber, Micheal R. Brown, and Kirsten Day (1999). “Multiobjective Urban Planning Using Genetic Algorithm”. In: *Journal of Urban Planning and Development* 125.2, pp. 86–99.

Batty, Michael (1982). “The Quest for the Qualitative: New Directions in Planning Theory and Analysis”. In: *Urban Policy and Research* 1.1, pp. 15–23. DOI: 10.1080/08222248208522670. URL: http://www.complexcity.info/files/2011/11/BATTY-UPR-1982.pdf.

– (2009). “Urban Modeling”. In: *International Encyclopedia of Human Geography. Oxford, UK: Elsevier*. Oxford, England: Elsevier, pp. 51–58. URL: http://www.casa.ucl.ac.uk/rits/BATTY-Urban-Modelling-2009.pdf.

– (2016). “Evolving a Plan: Design and Planning with Complexity”. In: *Complexity, Cognition, Urban Planning and Design*. Springer Proceedings in Complexity. Springer, Cham, pp. 21–42. ISBN: 978-3-319-32651-1 978-3-319-32653-5. DOI: 10.1007/978-3-319-32653-5_2. URL: https://link.springer.com/chapter/10.1007/978-3-319-32653-5_2.

Batty, Michael and Stephen Marshall (2012). “The Origins of Complexity Theory in Cities and Planning”. In: *Complexity Theories of Cities Have Come of Age*. Springer, Berlin, Heidelberg, pp. 21–45. ISBN: 978-3-642-24543-5 978-3-642-24544-2. DOI: 10.1007/978-3-642-24544-2_3. URL: https://link.springer.com/chapter/10.1007/978-3-642-24544-2_3.

Benson, Earl D., Julia L. Hansen, Arthur L. Schwartz, and Greg T. Smersh (1998). “Pricing Residential Amenities: The Value of a View”. In: *The Journal of Real Estate Finance and Economics* 16.1, pp. 55–73. ISSN: 1573-045X. DOI: 10.1023/A:1007785315925. URL: http://dx.doi.org/10.1023/A:1007785315925.

Best, Robert E., Forest Flager, and Michael D. Lepech (2015). “Modeling and Optimization of Building Mix and Energy Supply Technology for Urban Districts”. In: *Applied Energy* 159, pp. 161–177. ISSN: 03062619. DOI: 10.1016/j.apenergy.2015.08.076. URL: http://linkinghub.elsevier.com/retrieve/pii/S0306261915010120.

Bettencourt, L. M. A., J. Lobo, and G. B. West (2008). “Why Are Large Cities Faster? Universal Scaling and Self-Similarity in Urban Organization and Dynamics”. In: *The European Physical Journal B* 63.3, pp. 285–293. ISSN: 1434-6028, 1434-6036. DOI: 10.1140/epjb/e2008-00250-6. URL: http://link.springer.com/article/10.1140/epjb/e2008-00250-6.

Bhatta, Basudeb (2010). "Causes and Consequences of Urban Growth and Sprawl". In: *Analysis of Urban Growth and Sprawl from Remote Sensing Data*. Advances in Geographic Information Science. Springer, Berlin, Heidelberg, pp. 17–36. ISBN: 978-3-642-05298-9 978-3-642-05299-6. DOI: 10.1007/978-3-642-05299-6_2. URL: https://link.springer.com/chapter/10.1007/978-3-642-05299-6_2.

Bierlaire, Michel (2015). *Optimization: Principles and Algorithms*. Lausanne, Switzerland: EPFL Press. ISBN: 978-2-940222-78-0. URL: https://infoscience.epfl.ch/record/211191?ln=en.

Birch, Eugenie and Susan Wachter (2008). *Growing Greener Cities: Urban Sustainability in the Twenty-First Century*. University of Pennsylvania Press.

Black, Paul E. (2006). *Manhattan Distance*. In: *Dictionary of Algorithms and Data Structures*. National Institute of Standard and Technology. URL: https://xlinux.nist.gov/dads/HTML/manhattanDistance.html.

Bochatay, Denis, Isabelle Blanc, Olivier Jolliet, François Maréchal, Tiana Manasse-Ratsimandresy, and Rémy Beck (2005). *Projet PACOGEN, Evaluation Économique et Environnementale de Systèmes Énergétiques à Usage Résidentiel*. URL: http://infoscience.epfl.ch/record/59329.

Bradbury, Mason, M. Nils Peterson, and Jianguo Liu (2014). "Long-Term Dynamics of Household Size and Their Environmental Implications". In: *Population and Environment* 36.1, pp. 73–84. ISSN: 0199-0039, 1573-7810. DOI: 10.1007/s11111-014-0203-6. URL: https://link.springer.com/article/10.1007/s11111-014-0203-6.

Branke, Jürgen (2008). *Multiobjective Optimization: Interactive and Evolutionary Approaches*. Lecture notes in computer science, State-of-the-art survey 5252. Berlin ; New York: Springer. 470 pp. ISBN: 978-3-540-88907-6.

Brody, Samuel (2013). "The Characteristics, Causes, and Consequences of Sprawling Development Patterns in the United States". In: *Nature Education Knowledge* 4.5, p. 2. URL: https://www.nature.com/scitable/knowledge/library/the-characteristics-causes-and-consequences-of-sprawling-103014747.

Brueckner, Jan K. (2000). "Urban Sprawl: Diagnosis and Remedies". In: *International Regional Science Review* 23.2, pp. 160–171. ISSN: 0160-0176. DOI: 10.1177/016001700761012710. URL: https://doi.org/10.1177/016001700761012710.

Bruno, Michele, Kerri Henderson, and Hong Min Kim (2011). "Multi-Objective Optimization in Urban Design". In: *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design*. Boston, Massachusetts: Society for Computer Simulation International, pp. 102–109.

Building and Construction Authority (2016). *Building Energy Benchmarking Report*. Singapore: Building and Construction Authority, p. 40. URL: https://www.bca.gov.sg/GreenMark/others/BCA_BEBR_Abridged_FA_2016.pdf.

Burhenne, Sebastian, Dirk Jacob, and Gregor P. Henze (2011). "Sampling Based on Sobol' Sequences for Monte Carlo Techniques Applied to Building Simulations". In: *Proceedings of Building Simulation 2011*. 12th Conference of International Building

Performance Simulation Association. Sydney. URL: www.ibpsa.org/proceedings/BS2011/P_1590.pdf.

C40 Cities (2018). *C40 : Cities Urged to Step Up Climate Action and Ambition Ahead of Global Climate Action Summit.* URL: https://www.c40.org/other/cities-urged-to-step-up-climate-action-and-ambition-ahead-of-global-climate-action-summit.

Cajot, Sébastien (2018). "Interactive Optimization for Supporting Multicriteria Decisions in Urban and Energy System Planning". PhD thesis. Lausanne, Switzerland: EPFL.

Cajot, Sébastien, Markus Peter, Jean-Marie Bahu, Andreas Koch, and François Maréchal (2015). "Energy Planning in the Urban Context: Challenges and Perspectives". In: *Energy Procedia* 78, pp. 3366–3371. ISSN: 18766102. DOI: 10.1016/j.egypro.2015.11.752. URL: http://linkinghub.elsevier.com/retrieve/pii/S1876610215024844.

Cajot, Sébastien, Nils Schüler, Markus Peter, Andreas Koch, and François Maréchal (2017). "Interactive Optimization for the Planning of Urban Systems". In: *Energy Procedia.* CISBAT: Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale. Ed. by Jean-Louis Scartezzini. Vol. 122. Lausanne, Switzerland: Elsevier, pp. 445–450. DOI: 10.1016/j.egypro.2017.07.383. URL: http://linkinghub.elsevier.com/retrieve/pii/S1876610217329879.

– (2018). "Interactive Optimization with Parallel Coordinates: Exploring Multidimensional Spaces for Decision Support". In: *submitted to Frontiers in ICT*.

Chaturvedi, Kanishk, Carl Stephen Smyth, Gilles Gesquière, Tatjana Kutzner, and Thomas H. Kolbe (2017). "Managing Versions and History Within Semantic 3D City Models for the Next Generation of CityGML". In: *Advances in 3D Geoinformation.* Lecture Notes in Geoinformation and Cartography. Springer, Cham, pp. 191–206. ISBN: 978-3-319-25689-4 978-3-319-25691-7. DOI: 10.1007/978-3-319-25691-7_11. URL: https://link.springer.com/chapter/10.1007/978-3-319-25691-7_11.

Chen, Jie (2007). "Rapid Urbanization in China: A Real Challenge to Soil Protection and Food Security". In: *CATENA*. Influences of rapid urbanization and industrialization on soil resource and its quality in China 69.1, pp. 1–15. ISSN: 0341-8162. DOI: 10.1016/j.catena.2006.04.019. URL: http://www.sciencedirect.com/science/article/pii/S0341816206000920.

CityGML (2018a). *Cities around the World with Open Datasets.* URL: https://www.citygml.org/3dcities/.

– (2018b). *CityGML v3.0.* URL: https://www.citygml.org/ongoingdev/v3/.

Commission, European (2014). *A Policy Framework for Climate and Energy in the Period from 2020 to 2030.* Communication from the commision to the European parliament, the council, the European economic and social committee and the committee of the regions. Brussels: European Commission, p. 18.

CPLEX (2014). Version 12.6.0. IBM. URL: http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/.

Crawford, Ronald James (2016). *What Can Complexity Theory Tell Us about Urban Planning?* New Zealand Productivity Commission, Te Kōmihana Whai Hua o Aotearoa,

p. 18. URL: https://pdfs.semanticscholar.org/d58b/01f11701760d078c2ba95de0aa4b1aad00a2.pdf.

De Almeida, Aníbal, Paula Fonseca, Barbara Schlomann, and Nicolai Feilberg (2011). "Characterization of the Household Electricity Consumption in the EU, Potential Energy Savings and Specific Policy Recommendations". In: *Energy and Buildings* 43.8, pp. 1884–1894. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2011.03.027. URL: http://www.sciencedirect.com/science/article/pii/S0378778811001058.

Desthieux, Gilles (2005). "Approche systémique et participative du diagnostic urbain". PhD thesis. Lausanne: EPFL. URL: http://infoscience.epfl.ch/record/33684.

Desthieux, Gilles, Peter Gallinelli, and Reto Camponovo (2014). *Analyse Du Potentiel de Production Énergétique Par Les Panneaux Solaires Thermique et PV*. Rapport final 2. Geneva: hepia.

deVries, Bauke, Vincent Tabak, and Henri Achten (2005). "Interactive Urban Design Using Integrated Planning Requirements Control". In: *Automation in Construction* 14.2, pp. 207–213. ISSN: 09265805. DOI: 10.1016/j.autcon.2004.07.006. URL: http://linkinghub.elsevier.com/retrieve/pii/S0926580504000767.

Duarte, Carlos, Paul Raftery, and Stefano Schiavon (2016). "SinBerBEST Technology Energy Assessment Report". In: URL: https://escholarship.org/uc/item/7k1796zv.

Eidgenössische Elektrizitätskommission (2016). *Strompreis-Webseite Der ElCom: Vergleichen Sie Ihren Strompreis*. URL: https://www.strompreis.elcom.admin.ch/Map/ShowSwissMap.aspx.

Eidgenössisches Departement für Wirtschaft, Bildung und Forschung (2016). *Eidg. Volkswirtschaftsdepartement EVD - Preisüberwachung*. URL: http://gaspreise.preisueberwacher.ch/web/index.asp?z=9.

EnDK (2014). *Mustervorschriften der Kantone im Energiebereich (MuKEn)*. URL: https://www.endk.ch/de/ablage/grundhaltung-der-endk/muken2014-d20150109-2.pdf.

Energy Market Authority (2016). *Singapore Energy Statistics 2016*. Singapore: Energy Market Authority, p. 64. URL: https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/SES%202016/Publication_Singapore_Energy_Statistics_2016.pdf.

EnergyPlus. *Weather Data*. URL: https://energyplus.net/weather.

Evans, Alan W. and Oliver Marc Hartwich (2006). *Better Homes, Greener Cities*. Policy Exchange London.

Fazlollahi, Samira (2014). "Decomposition Optimization Strategy for the Design and Operation of District Energy Systems". Lausanne: EPFL. URL: http://infoscience.epfl.ch/record/197534?ln=en.

Federal Office of Meteorology and Climatology (2017). *MeteoSwiss IDAWEB: Welcome at IDAWEB!* URL: https://gate.meteoswiss.ch/idaweb/system/welcome.do.

Ferreira, Nivan, Marcos Lage, Harish Doraiswamy, Huy Vo, Luc Wilson, Heidi Werner, Muchan Park, and Claudio Silva (2015). "Urbane: A 3D Framework to Support Data Driven Decision Making in Urban Development". In: *Visual Analytics Science and Technology (VAST), 2015 IEEE Conference On*. Ed. by Min Chen and Gennady

Andrienko. IEEE, pp. 97–104. URL: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7347636.

F.J. Fernández, L.J. Alvarez-Vázquez, N. García-Chan, A. Martínez, and M.E. Vázquez-Méndez (2015). "Optimal Location of Green Zones in Metropolitan Areas to Control the Urban Heat Island". In: *Journal of Computational and Applied Mathematics* 289, pp. 412–425. ISSN: 03770427. DOI: 10.1016/j.cam.2014.10.023. URL: http://linkinghub.elsevier.com/retrieve/pii/S0377042714004695.

Floudas, Christodoulos A. (1995). *Nonlinear and Mixed-Integer Optimization*. New York: Oxford University Press, Inc. URL: https://books.google.com/books/about/Nonlinear_and_Mixed_Integer_Optimization.html?id=OhTfOjSkq18C.

– (2000). *Deterministic Global Optimization*. Red. by Panos Pardalos and Reiner Horst. Vol. 37. Nonconvex Optimization and Its Applications. Boston, MA: Springer US. ISBN: 978-1-4419-4820-5 978-1-4757-4949-6. DOI: 10.1007/978-1-4757-4949-6. URL: http://link.springer.com/10.1007/978-1-4757-4949-6.

Fonseca, Jimeno A., Laura Estévez-Mauriz, Claudiu Forgaci, and Nils Björling (2017). "Spatial Heterogeneity for Environmental Performance and Resilient Behavior in Energy and Transportation Systems". In: *Computers, Environment and Urban Systems* 62, pp. 136–145. ISSN: 01989715. DOI: 10.1016/j.compenvurbsys.2016.11.001. URL: http://linkinghub.elsevier.com/retrieve/pii/S0198971516303568.

ForêtSuisse (2017). *Marché du bois*. URL: http://www.energie-bois.ch/fileadmin/user_resources/01_Holzenergie/Energieholz_Richtpreise/1712_La_Foret_prix_bois-energie.pdf.

Forever Fuels (2016). *Future Prospects for Wood Pellet Prices and Availability*. URL: https://www.forever-fuels.com/future-prospects-wood-pellet-prices-and-availability.

Foucquier, Aurélie, Sylvain Robert, Frédéric Suard, Louis Stéphan, and Arnaud Jay (2013). "State of the Art in Building Modelling and Energy Performances Prediction: A Review". In: *Renewable and Sustainable Energy Reviews* 23, pp. 272–288. ISSN: 1364-0321. DOI: 10.1016/j.rser.2013.03.004. URL: http://www.sciencedirect.com/science/article/pii/S1364032113001536.

Fourer, Robert (2014). *AMPL*. Version 20140224.

Frischknecht, Rolf, René Itten, and Karin Flury (2012). *Treibhausgas-Emissionen Schweizer Strommixe*. v1.4. Uster, Switzerland: Bundesamt für Umwelt BAFU. URL: http://www.bafu.admin.ch/klima/09608/index.html?lang=de&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Yuq2Z6gpJCGfIF5fWym162epYbg2c_JjKbNoKSn6A--.

Gal, Tomas (1995). *Postoptimal Analyses, Parametric Programming, and Related Topics*. 2nd ed. 1995. Reprint 2010. Berlin, Boston: De Gruyter. ISBN: 978-3-11-087120-3. DOI: 10.1515/9783110871203. URL: https://www.degruyter.com/viewbooktoc/product/143242.

"Complexity" (2008). "Complexity: 5 Questions". In: *Automatic Press*. Ed. by Carlos Gershenson.

Gilbert, Nigel (2008). *Agent-Based Models*. 153. Sage.

Girardin, Luc (2012). “A GIS-Based Methodology for the Evaluation of Integrated Energy Systems in Urban Area”. Lausanne: EPFL.

Gladwell, Malcolm (2002). *The Tipping Point: How Little Things Can Make a Big Difference*. Boston: Back Bay Books. 301 pp. ISBN: 978-0-316-34662-7.

Godschalk, David R. and William E. Mills (1966). “A Collaborative Approach to Planning Through Urban Activities”. In: *Journal of the American Institute of Planners* 32.2, pp. 86–95. ISSN: 0002-8991. DOI: 10.1080/01944366608979362. URL: http://www.tandfonline.com/doi/abs/10.1080/01944366608979362.

Gröger, Gerhard, Thomas H. Kolbe, Claus Nagel, and Karl-Heinz Häfele (2012). *OGC City Geography Markup Language (CityGML) Encoding Standard*. URL: https://portal.opengeospatial.org/files/?artifact_id=47842.

Guerra Santin, Olivia, Laure Itard, and Henk Visscher (2009). “The Effect of Occupancy and Building Characteristics on Energy Use for Space and Water Heating in Dutch Residential Stock”. In: *Energy and Buildings* 41.11, pp. 1223–1232. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2009.07.002. URL: http://www.sciencedirect.com/science/article/pii/S0378778809001388.

Haimes, Y. Y., Leon Lasdon, and D. A. Wismer (1971). “On a Bicriterion Formulation of the Problems of Integrated System Identification and System Optimization”. In: *IEEE Transactions on Systems, Man, and Cybernetics - TSMC* 1, pp. 296–297. DOI: 10.1109/TSMC.1971.4308298.

Hair, J.F. (2006). *Multivariate Data Analysis*. Upper Saddle River, NJ [etc.]: Pearson Prentice Hall. ISBN: 0-13-032929-0.

Haken, Hermann and Juval Portugali (2015). *Information Adaptation: The Interplay Between Shannon Information and Semantic Information in Cognition*. SpringerBriefs in Complexity. Springer International Publishing. ISBN: 978-3-319-11169-8. URL: //www.springer.com/gp/book/9783319111698.

Hall, Peter (2014). *Cities of Tomorrow: An Intellectual History of Urban Planning and Design since 1880*. 4th ed. Chichester, West Sussex, UK: John Wiley & Sons.

Haque, Afsana and Yasushi Asami (2014). “Optimizing Urban Land Use Allocation for Planners and Real Estate Developers”. In: *Computers, Environment and Urban Systems* 46, pp. 57–69. ISSN: 01989715. DOI: 10.1016/j.compenvurbsys.2014.04.004. URL: http://linkinghub.elsevier.com/retrieve/pii/S0198971514000477.

Henchoz, Samuel (2016). “Potential of Refrigerant Based District Heating and Cooling Networks”. PhD thesis. Lausanne: EPFL.

Hillier, Bill (2012). “The Genetic Code for Cities: Is It Simpler than We Think?” In: *Complexity Theories of Cities Have Come of Age*. Springer, Berlin, Heidelberg, pp. 129–152. ISBN: 978-3-642-24543-5 978-3-642-24544-2. DOI: 10.1007/978-3-642-24544-2_8. URL: https://link.springer.com/chapter/10.1007/978-3-642-24544-2_8.

Hollander, Justin B., Karina Pallagst, Terry Schwarz, and Frank J. Popper (2009). “Planning Shrinking Cities”. In: *Progress in planning* 72.4, pp. 223–232.

Hovestadt, Ludger (2010). *Kaisersrot - Solutions You Cannot Draw*. URL: http://www.kaisersrot.ch/kaisersrot-02/Welcome.html.

Hsieh, Shanshan, Nils Schüler, Zhongming Shi, Jimeno A. Fonseca, François Maréchal, and Arno Schlueter (2017). "Defining Density and Land Uses under Energy Performance Targets at the Early Stage of Urban Planning Processes". In: *CISBAT*. Lausanne, Switzerland.

Huang, Zishuo, Hang Yu, Zhenwei Peng, and Mei Zhao (2015). "Methods and Tools for Community Energy Planning: A Review". In: *Renewable and Sustainable Energy Reviews* 42, pp. 1335–1348. ISSN: 13640321. DOI: 10.1016/j.rser.2014.11.042. URL: http://linkinghub.elsevier.com/retrieve/pii/S1364032114009733.

Hwang, Ching-Lai and Abu Syed Md. Masud (1979). *Multiple Objective Decision Making—Methods and Applications: A State-of-the-Art Survey*. Vol. 164. Lecture Notes in Economics and Mathematical Systems. Berlin, Heidelberg, New York: Springer. ISBN: 978-3-540-09111-0.

Jacobs, Jane (1961). *The Death and Life of Great American Cities*. New York, USA: Vintage Books. 466 pp. ISBN: 978-0-679-74195-4.

Jansen, Gijsbertus R. M. (1993). "Commuting: Home Sprawl, Job Sprawl, Traffic Jams". In: *A Billion Trips a Day*. Transportation Research, Economics and Policy. Springer, Dordrecht, pp. 101–127. ISBN: 978-90-481-4278-1 978-94-015-8118-9. DOI: 10.1007/978-94-015-8118-9_7. URL: https://link.springer.com/chapter/10.1007/978-94-015-8118-9_7.

Johnson, Jeffrey (2012). "Cities: Systems of Systems of Systems". In: *Complexity Theories of Cities Have Come of Age*. Springer, Berlin, Heidelberg, pp. 153–172. ISBN: 978-3-642-24543-5 978-3-642-24544-2. DOI: 10.1007/978-3-642-24544-2_9. URL: https://link.springer.com/chapter/10.1007/978-3-642-24544-2_9.

Jones, Rory V. and Kevin J. Lomas (2016). "Determinants of High Electrical Energy Demand in UK Homes: Appliance Ownership and Use". In: *Energy and Buildings* 117, pp. 71–82. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2016.02.020. URL: http://www.sciencedirect.com/science/article/pii/S0378778816300676.

Kac, Mark (1969). "Some Mathematical Models in Science". In: *Science* 166.3906, pp. 695–699. ISSN: 0036-8075. JSTOR: 1727775.

Kämpf, Jérôme Henri (2009). "On the Modelling and Optimisation of Urban Energy Fluxes". Lausanne, Switzerland: EPFL.

Kämpf, Jérôme Henri, Marylène Montavon, Josep Bunyesc, Raffaele Bolliger, and Darren Robinson (2010). "Optimisation of Buildings' Solar Irradiation Availability". In: *Solar Energy* 84.4, pp. 596–603. ISSN: 0038092X. DOI: 10.1016/j.solener.2009.07.013. URL: http://linkinghub.elsevier.com/retrieve/pii/S0038092X09001819.

Keirstead, James, Nouri Samsatli, and Nilay Shah (2009). "SynCity: An Integrated Toolkit for Urban Energy Systems Modelling". In: *Energy Efficient Cities: Assessment Tools and Benchmarking Practices*. Fifth Urban Research Symposium. Ed. by Ranjan K. Bose. Marseille, France: The World Bank. DOI: 10.1596/978-0-8213-8104-5.

Keirstead, James, Nouri Samsatli, Nilay Shah, and Céline Weber (2012). "The Impact of CHP (Combined Heat and Power) Planning Restrictions on the Efficiency of Urban Energy Systems". In: *Energy*. 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2010 41.1, pp. 93–103. ISSN: 0360-5442. DOI: 10.1016/j.energy.2011.06.011. URL: http://www.sciencedirect.com/science/article/pii/S0360544211003884.

Keirstead, James and Nilay Shah (2011). "Calculating Minimum Energy Urban Layouts with Mathematical Programming and Monte Carlo Analysis Techniques". In: *Computers, Environment and Urban Systems*. Sustainable Urban Development 35.5, pp. 368–377. ISSN: 0198-9715. DOI: 10.1016/j.compenvurbsys.2010.12.005. URL: http://www.sciencedirect.com/science/article/pii/S0198971511000032.

– (2013). "The Changing Role of Optimization in Urban Planning". In: *Optimization, Simulation, and Control*. Ed. by Altannar Chinchuluun, Panos M. Pardalos, Rentsen Enkhbat, and E. N. Pistikopoulos. Vol. 76. Springer Optimization and Its Applications. New York, NY: Springer New York, pp. 175–193. ISBN: 978-1-4614-5130-3 978-1-4614-5131-0. URL: http://link.springer.com/10.1007/978-1-4614-5131-0.

Kellenberger, Daniel, Martin Ménard, Stefan Schneider, and Martin Hänger (2012). *Arealentwicklung für die 2000-Watt- Gesellschaft: Beurteilungsmethode in Anlehnung an den SIA-Effizienzpfad Energie*. Schlussbericht. Bern, Schweiz: Bundesamt für Energie BFE.

Keynes, J. M. (1937). "The General Theory of Employment". In: *The Quarterly Journal of Economics* 51.2, pp. 209–223. ISSN: 0033-5533. DOI: 10.2307/1882087. URL: https://academic.oup.com/qje/article/51/2/209/1939387.

Kiureghian, Armen Der and Ove Ditlevsen (2009). "Aleatory or Epistemic? Does It Matter?" In: *Structural Safety* 31.2, pp. 105–112.

Koffka, Kurt (1935). *Principles Of Gestalt Psychology*. Routledge. ISBN: 978-1-136-30681-5. DOI: 10.4324/9781315009292. URL: https://www.taylorfrancis.com/books/9781136306815.

Kolbe, Thomas H., Zhihang Yao, Claus Nagel, Richard Redweik, Philipp Willkomm, György Hudra, Arda Müftüoglu, and Felix Kunde (2016). *3D City Database for CityGML*. URL: https://github.com/3dcitydb/3dcitydb/blob/master/Documentation/3DCityDB_Documentation_v3.3.pdf.

Kolter, J. Zico and Joseph Ferreira (2011). "A Large-Scale Study on Predicting and Contextualizing Building Energy Usage." In: *AAAI*. URL: http://www.aaai.org/ocs/index.php/AAAI/AAAI11/paper/download/3759/4088.

Kumar, Piyush, Jay M. Rosenberger, and Gazi Md Daud Iqbal (2016). "Mixed Integer Linear Programming Approaches for Land Use Planning That Limit Urban Sprawl". In: *Computers & Industrial Engineering* 102, pp. 33–43. ISSN: 03608352. DOI: 10.1016/j.cie.2016.10.007. URL: http://linkinghub.elsevier.com/retrieve/pii/S036083521630376X.

Kwartler, Michael (1998). "Regulating the Good You Can't Think Of". In: *URBAN DESIGN International* 3.1-2, pp. 13–21. ISSN: 1357-5317, 1468-4519. DOI: 10.1057/udi.1998.3. URL: https://link.springer.com/article/10.1057/udi.1998.3.

Lawler, E. L. and D. E. Wood (1966). "Branch-And-Bound Methods: A Survey". In: *Operations Research* 14.4, pp. 699–719. ISSN: 0030-364X. JSTOR: 168733.

Le grand conseil de la république et canton de Genève (1988). *Loi sur les constructions et les installations diverses (LCI).* URL: http://www.ge.ch/legislation/rsg/f/s/rsg_L5_05.html.

Lewes, George Henry (1875). *Problems of Life and Mind.* Vol. 2. Trübner & Co.

Ligmann-Zielinska, Arika, Richard Church, and Piotr Jankowski (2005). "Sustainable Urban Land Use Allocation with Spatial Optimization". In: *Conference Proceedings. The 8th International Conference on Geocomputation.* 8th International Conference on GeoComputation. Michigan, USA, pp. 1–3. URL: http://www.academia.edu/download/5517709/10.1.1.108.277.pdf.

– (2008). "Spatial Optimization as a Generative Technique for Sustainable Multiobjective Land-Use Allocation". In: *International Journal of Geographical Information Science* 22.6, pp. 601–622. ISSN: 1365-8816. DOI: 10.1080/13658810701587495. URL: http://www.informaworld.com/openurl?genre=article&doi=10.1080/13658810701587495&magic=crossref%7C%7CD404A21C5BB053405B1A640AFFD44AE3.

Lineweaver, Charles H., Paul C. W. Davies, and Michael Ruse (2013). "What Is Complexity? Is It Increasing?" In: *Complexity and the Arrow of Time.* Cambridge University Press, pp. 3–16. ISBN: 978-1-107-02725-1.

Liu, Jianguo, Gretchen C. Daily, Paul R. Ehrlich, and Gary W. Luck (2003). "Effects of Household Dynamics on Resource Consumption and Biodiversity". In: *Nature* 421.6922, pp. 530–533. ISSN: 1476-4687. DOI: 10.1038/nature01359. URL: https://www.nature.com/articles/nature01359.

Liu, Pei, Michael C. Georgiadis, and Efstratios N. Pistikopoulos (2011). "Advances in Energy Systems Engineering". In: *Industrial & Engineering Chemistry Research* 50.9, pp. 4915–4926. ISSN: 0888-5885, 1520-5045. DOI: 10.1021/ie101383h. URL: http://pubs.acs.org/doi/abs/10.1021/ie101383h.

Luther, Joachim, Thomas Reindl, D. K. S. Wang, A. Aberle, Wilfred Walsh, A. Nobre, and G. G. Yao (2013). "Solar Photovoltaic (PV) Roadmap for Singapore (A Summary)". In: *Solar Energy Research Institute of Singapore (SERIS): Singapore.*

Makridakis, Spyros G., Steven C. Wheelwright, and Rob J. Hyndman (1997). *Forecasting: Methods and Applications.* 3rd ed. New York: Wiley. 656 pp. ISBN: 978-0-471-53233-0.

Manandhar, U., A. Ukil, and D. Wang (2015). "Building HVAC Load Profiling Using EnergyPlus". In: *2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA).* 2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), pp. 1–6. DOI: 10.1109/ISGT-Asia.2015.7386983.

Mani, Akshay (2013). *On the Move: The Global Rise of Mass Transit.* URL: http://thecityfix.com/blog/on-the-move-global-rise-mass-transit-akshay-mani/.

Marcotullio, Peter John, Andrea Sarzynski, Jochen Albrecht, Niels Schulz, and Jake Garcia (2013). "The Geography of Global Urban Greenhouse Gas Emissions: An Exploratory Analysis". In: *Climatic Change* 121.4, pp. 621–634. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-013-0977-z. URL: https://link.springer.com/article/10.1007/s10584-013-0977-z.

Markovic, Dragan, Dragan Cvetkovic, and Branislav Masic (2011). “Survey of Software Tools for Energy Efficiency in a Community”. In: *Renewable and Sustainable Energy Reviews* 15.9, pp. 4897–4903. ISSN: 13640321. DOI: 10.1016/j.rser.2011.06.014. URL: http://linkinghub.elsevier.com/retrieve/pii/S1364032111003078.

Marler, R. Timothy and Jasbir S. Arora (2010). “The Weighted Sum Method for Multi-Objective Optimization: New Insights”. In: *Structural and Multidisciplinary Optimization* 41.6, pp. 853–862. ISSN: 1615-147X, 1615-1488. DOI: 10.1007/s00158-009-0460-7. URL: https://link.springer.com/article/10.1007/s00158-009-0460-7.

Marshall, Stephen (2012). “Planning, Design and the Complexity of Cities”. In: *Complexity Theories of Cities Have Come of Age*. Springer, Berlin, Heidelberg, pp. 191–205. ISBN: 978-3-642-24543-5 978-3-642-24544-2. DOI: 10.1007/978-3-642-24544-2_11. URL: https://link.springer.com/chapter/10.1007/978-3-642-24544-2_11.

Mastrucci, Alessio, Olivier Baume, Francesca Stazi, and Ulrich Leopold (2014). “Estimating Energy Savings for the Residential Building Stock of an Entire City: A GIS-Based Statistical Downscaling Approach Applied to Rotterdam”. In: *Energy and Buildings* 75, pp. 358–367. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2014.02.032. URL: http://www.sciencedirect.com/science/article/pii/S0378778814001467.

McPherson, Guy (2003). “It’s the End of the World as We Know It (and I Feel Fine): Rent Regulation in New York City and the Unanswered Questions of Market and Society”. In: *Fordham Law Review* 72, p. 1125. URL: https://heinonline.org/HOL/Page?handle=hein.journals/flr72&id=1143&div=&collection=.

Meadows, Donella (1998). *Indicators and Information Systems for Sustainable Development*. Hartland, Vermont, USA: The Sustainability Institute, p. 95. URL: https://www.iisd.org/pdf/s_ind_2.pdf.

Meggers, Forrest, Volker Ritter, Philippe Goffin, Marc Baetschmann, and Hansjürg Leibundgut (2012). “Low Exergy Building Systems Implementation”. In: *Energy*. 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2010 41.1, pp. 48–55. ISSN: 0360-5442. DOI: 10.1016/j.energy.2011.07.031. URL: http://www.sciencedirect.com/science/article/pii/S0360544211004798.

Meier, Ruedi (2015). *Wirtschaftlichkeit energetischer Sanierungsmassnahmen - Modellrechnungen für Ein- und Mehrfamilienhäuser*. Bern, Switzerland: energie-cluster.ch, p. 121. URL: https://www.energie-cluster.ch/admin/data/files/file/file/1291/20160429-bfe-wirtschaftlichkeit-energetischer-sanierungsmassnahmen_.pdf?lm=1464330144.

Mills, Ian (2014). “On the Use of Italic and Roman Fonts for Symbols in Scientific Text”. In: *Chemistry International* 36.5, p. 23. ISSN: 13652192. DOI: 10.1515/ci-2014-0529. URL: https://www.degruyter.com/view/j/ci.2014.36.issue-5/ci-2014-0529/ci-2014-0529.xml.

Minergie (2017). *Produktreglement zu den Gebäudestandards MINERGIE/MINERGIE-P/MINERGIE-A - Version 2017.3*. norm. Minergie Schweiz. URL: https://www.minergie.ch/media/171215_produktreglement_minergie_p_a_v2017.3_de.pdf.

Mirakyan, Atom and Roland De Guio (2013). "Integrated Energy Planning in Cities and Territories: A Review of Methods and Tools". In: *Renewable and Sustainable Energy Reviews* 22, pp. 289–297. ISSN: 13640321. DOI: 10.1016/j.rser.2013.01.033. URL: http://linkinghub.elsevier.com/retrieve/pii/S1364032113000646.

– (2016). *Three Domain Modelling and Uncertainty Analysis*. Springer.

Moret, Stefano (2017). "Strategic Energy Planning under Uncertainty". PhD thesis. Lausanne: EPFL. 269 pp. URL: https://infoscience.epfl.ch/record/231814?ln=en.

Moret, Stefano, Emanuela Peduzzi, Léda Gerber, and François Maréchal (2016). "Integration of Deep Geothermal Energy and Woody Biomass Conversion Pathways in Urban Systems". In: *Energy Conversion and Management* 129, pp. 305–318. ISSN: 01968904. DOI: 10.1016/j.enconman.2016.09.079. URL: http://linkinghub.elsevier.com/retrieve/pii/S0196890416308780.

Moudon, Anne Vernez (2009). "Real Noise from the Urban Environment: How Ambient Community Noise Affects Health and What Can Be Done About It". In: *American Journal of Preventive Medicine* 37.2, pp. 167–171. ISSN: 0749-3797. DOI: 10.1016/j.amepre.2009.03.019. URL: http://www.sciencedirect.com/science/article/pii/S0749379709002955.

Nasser, Noha (2003). "Planning for Urban Heritage Places: Reconciling Conservation, Tourism, and Sustainable Development". In: *Journal of Planning Literature* 17.4, pp. 467–479. ISSN: 0885-4122. DOI: 10.1177/0885412203017004001. URL: https://doi.org/10.1177/0885412203017004001.

Nationalbank, Schweizerische (2017). *Zinssätze, Renditen und Devisenmarkt*. URL: https://data.snb.ch/de/topics/ziredev?_escaped_fragment_=/doc/explanations_ziredev#!/cube/zikreddet?fromDate=2016-01&toDate=2016-12&dimSel=D0(K,OBB,MBB,FH,FI).

Neema, Meher Nigar and Akira Ohgai (2010). "Multi-Objective Location Modeling of Urban Parks and Open Spaces: Continuous Optimization". In: *Computers, Environment and Urban Systems* 34.5, pp. 359–376. ISSN: 01989715. DOI: 10.1016/j.compenvurbsys.2010.03.001. URL: http://linkinghub.elsevier.com/retrieve/pii/S0198971510000207.

– (2013). "Multitype Green-Space Modeling for Urban Planning Using GA and GIS". In: *Environment and Planning B: Planning and Design* 40.3, pp. 447–473. ISSN: 0265-8135, 1472-3417. DOI: 10.1068/b38003. URL: http://journals.sagepub.com/doi/10.1068/b38003.

Oberdieck, Richard, Nikolaos A. Diangelakis, Ioana Nascu, Maria M. Papathanasiou, Muxin Sun, Styliani Avraamidou, and Efstratios N. Pistikopoulos (2016). "On Multi-Parametric Programming and Its Applications in Process Systems Engineering". In: *Chemical Engineering Research and Design*. Process Systems Engineering - A Celebration in Professor Roger Sargent's 90th Year 116, pp. 61–82. ISSN: 0263-8762. DOI: 10.1016/j.cherd.2016.09.034. URL: http://www.sciencedirect.com/science/article/pii/S0263876216303276.

OCSTAT (2009a). *Population, logements, nombre de pièces et taux d'occupation dans les bâtiments à plusieurs logements, par commune, en 2009.* URL: http://www.ge.ch/statistique/tel/domaines/09/09_03/T_09_03_1_08.xls.

– (2009b). *Population, logements, nombre de pièces et taux d'occupation pour les maisons individuelles et les maisons à deux logements, par commune, en 2009.* URL: http://www.ge.ch/statistique/tel/domaines/09/09_03/T_09_03_1_11.xls.

OFEV (2016). "Référentiel de 6 % pour les réseaux de chauffage à distance". In: *Newsletter sur la compensation des émissions de CO2 en Suisse. 6*, online. URL: https://www.bafu.admin.ch/bafu/fr/home/themes/climat/newsletter/newsletters---compensation-des-emissions-de-co2--/7e-newsletter-sur-la-compensation-des-emissions-de-co2-en-suisse.html.

Office de l'urbanisme (2011). *Plan directeur cantonal - Etude des besoins et de l'offre en logements / septembre 2011.* Genève: Département des constructions et des technologies de l'information, p. 33. URL: http://ge.ch/amenagement/media/amenagement/files/fichiers/images/documents/etude_des_besoins_et_de_l_offre_en_logements_light.pdf.

– (2013). *Plan directeur de quartier - Les Cherpines.* PDQ 29897. Genève: État de Genève and Commune de Confignon and Commune de Plan-les-Ouates. URL: http://ge.ch/amenagement/pdq-cherpines.

Oh, Seung Jin, Kim Choon Ng, Kyaw Thu, Wongee Chun, and Kian Jon Ernest Chua (2016). "Forecasting Long-Term Electricity Demand for Cooling of Singapore's Buildings Incorporating an Innovative Air-Conditioning Technology". In: *Energy and Buildings* 127, pp. 183–193. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2016.05.073. URL: http://www.sciencedirect.com/science/article/pii/S037877881630442X.

Pistikopoulos, Efstratios Nikolaou, Amparo Galindo, and Vivek Dua, eds. (2007). *Multi-Parametric Programming: Theory, Algorithms, and Applications.* Vol. 1. Process systems engineering. Weinheim: Wiley-VCH. 309 pp. ISBN: 978-3-527-31691-5.

Portugali, Juval (2016). "What Makes Cities Complex?" In: *Complexity, Cognition, Urban Planning and Design.* Springer Proceedings in Complexity. Springer, Cham, pp. 3–19. ISBN: 978-3-319-32651-1 978-3-319-32653-5. DOI: 10.1007/978-3-319-32653-5_1. URL: https://link.springer.com/chapter/10.1007/978-3-319-32653-5_1.

R Core Team (2013). *R: A Language and Environment for Statistical Computing.* Vienna, Austria: R Foundation for Statistical Computing. URL: http://www.R-project.org/.

Rakha, Tarek and Christoph F. Reinhart (2011). "Generative Urban Modeling: A Design Work Flow for Walkability-Optimized Cities". In: *Respecting Fragile Places: Proceedings of the 29th Conference on Education in Computer Aided Architectural Design in Europe, Ljubljana, Slovenia, September 21-24, 2011.* Conference on Education in Computer Aided Architectural Design in Europe. Ed. by Tadeja Zupančič-Strojan, Špela Verovšek, and Anja Jutraž. Ljubljana, Slovenia: eCAADe, Education and Research in Computer Aided Architectural Design in Europe ; Faculty of Architecture. ISBN: 978-94-91207-01-3.

Read, Stephen (2012). "Meaning and Material: Phenomenology, Complexity, Science and 'Adjacent Possible' Cities". In: *Complexity Theories of Cities Have Come of Age*. Springer, Berlin, Heidelberg, pp. 105–127. ISBN: 978-3-642-24543-5 978-3-642-24544-2. DOI: 10.1007/978-3-642-24544-2_7. URL: https://link.springer.com/chapter/10.1007/978-3-642-24544-2_7.

Reeves, Colin R., ed. (1993). *Modern Heuristic Techniques for Combinatorial Problems*. New York, USA: John Wiley & Sons, Inc. ISBN: 0-470-22079-1.

Reinhart, Christoph F. and Carlos Cerezo Davila (2016). "Urban Building Energy Modeling – A Review of a Nascent Field". In: *Building and Environment* 97, pp. 196–202. ISSN: 03601323. DOI: 10.1016/j.buildenv.2015.12.001. URL: http://linkinghub.elsevier.com/retrieve/pii/S0360132315003248.

Reinhart, Christoph F., Timur Dogan, J. Alstan Jakubiec, Tarek Rakha, and Andrew Sang (2013). "UMI - An Urban Simulation Environment for Building Energy Use, Daylighting and Walkability". In: *13th Conference of International Building Performance Simulation Association, Chambery, France*. URL: http://web.mit.edu/SustainableDesignLab/publications/umi_introduction.pdf.

Rey, Emmanuel and Sophie Lufkin (2013). "Durabilité à l'échelle Du Quartier". In: Lausanne: Architecture albums, pp. 161–178.

Rickles, Dean, Penelope Hawe, and Alan Shiell (2007). "A Simple Guide to Chaos and Complexity". In: *Journal of Epidemiology and Community Health* 61.11, pp. 933–937. ISSN: 0143-005X. DOI: 10.1136/jech.2006.054254. pmid: 17933949. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2465602/.

Riera Pérez, Maria Gracia and Emmanuel Rey (2013). "A Multi-Criteria Approach to Compare Urban Renewal Scenarios for an Existing Neighborhood. Case Study in Lausanne (Switzerland)". In: *Building and Environment* 65, pp. 58–70. ISSN: 03601323. DOI: 10.1016/j.buildenv.2013.03.017. URL: http://linkinghub.elsevier.com/retrieve/pii/S0360132313000978.

Robinson, Darren (2011). *Computer Modelling for Sustainable Urban Design : Physical Principles, Methods and Applications*. London: Earthscan. 277 pp. ISBN: 978-1-84407-679-6.

Robinson, Darren, N. Campbell, W. Gaiser, K. Kabel, A. Le-Mouel, N. Morel, J. Page, S. Stankovic, and A. Stone (2007). "SUNtool – A New Modelling Paradigm for Simulating and Optimising Urban Sustainability". In: *Solar Energy*. CISBAT 2005 81.9, pp. 1196–1211. ISSN: 0038-092X. DOI: 10.1016/j.solener.2007.06.002. URL: http://www.sciencedirect.com/science/article/pii/S0038092X0700120X.

Robinson, Darren, Frédéric Haldi, Philippe Leroux, Diane Perez, Adil Rasheed, and Urs Wilke (2009). "CITYSIM: Comprehensive Micro-Simulation of Resource Flows for Sustainable Urban Planning". In: *Proceedings of the Eleventh International IBPSA Conference*, pp. 1083–1090. URL: http://infoscience.epfl.ch/record/148717?ln=en.

Robinson, Darren and Andrew Stone (2004). "Irradiation Modelling Made Simple: The Cumulative Sky Approach and Its Applications". In: *PLEA Conference*. Built Environments and Environmental Buildings. Eindhoven, The Netherlands, pp. 19–22. URL: http://isites.harvard.edu/fs/docs/icb.topic978971.files/2004RobinsonAndStone.pdf.

Robinson, Darren, Urs Wilke, and Frédéric Haldi (2011). “Multi Agent Simulation of Occupants" Presence and Behaviour”. In: *Proceedings of Building Simulation 2011*, pp. 2110–2117. URL: http://infoscience.epfl.ch/record/174524?ln=en.

Roudsari, Mostapha Sadeghipour, Michelle Pak, and Adrian Smith (2013a). “Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design”. In: *Proceedings of the 13th International IBPSA Conference Held in Lyon, France Aug.* URL: http://www.ibpsa.org/proceedings/BS2013/p_2499.pdf.

– (2013b). “Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design”. In: *Proceedings of the 13th International IBPSA Conference Held in Lyon, France Aug.* URL: http://www.ibpsa.org/proceedings/BS2013/p_2499.pdf.

Roy, Bernard (1985). *Méthodologie multicritère d'aide à la décision.* Paris, France: Economica. 423 pp. ISBN: 978-2-7178-0901-5. URL: https://infoscience.epfl.ch/record/2914.

Rubin, Paul (2012). *Modeling Absolute Values.* URL: https://orinanobworld.blogspot.com/2012/07/modeling-absolute-values.html.

Russo, Patrizia, Rosa Lanzilotti, Maria F. Costabile, and Christopher J. Pettit (2018). “Towards Satisfying Practitioners in Using Planning Support Systems”. In: *Computers, Environment and Urban Systems* 67, pp. 9–20. ISSN: 0198-9715. DOI: 10.1016/j.compenvurbsys.2017.08.009. URL: http://www.sciencedirect.com/science/article/pii/S0198971517304143.

Ruzicka-Rossier, Monique (2005). “Développement territorial et urbanisme I”. EPFL.

Saleh, M. and K. Al-Hagla (2012). “Parametric Urban Comfort Envelope, an Approach toward a Responsive Sustainable Urban Morphology'”. In: *International journal of social, Human and Technology* 6, pp. 37–44. DOI: 10.1999/1307-6892/2433. URL: http://www.waset.org/publications/2433.

Salingaros, Nikos A. (2012). “Urbanism as Computation”. In: *Complexity Theories of Cities Have Come of Age.* Springer, Berlin, Heidelberg, pp. 245–268. ISBN: 978-3-642-24543-5 978-3-642-24544-2. DOI: 10.1007/978-3-642-24544-2_14. URL: https://link.springer.com/chapter/10.1007/978-3-642-24544-2_14.

Saltelli, A., Marco Ratto, Terry Andres, Francesca Campolongo, Jessica Cariboni, Debora Gatelli, Michaela Saisana, and Stefano Tarantola (2008). *Global Sensitivity Analysis: The Primer.* John Wiley & Sons. 307 pp. ISBN: 978-0-470-72517-7.

Schmidt, Dietrich (2009). “Low Exergy Systems for High-Performance Buildings and Communities”. In: *Energy and Buildings* 41.3, pp. 331–336. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2008.10.005. URL: http://www.sciencedirect.com/science/article/pii/S0378778808002223.

Schneider Benjamin, Richard Florida (2018). *It's Time to Acknowledge That the Housing Crisis Is Global.* URL: https://www.citylab.com/equity/2018/04/the-global-housing-crisis/557639/.

Schneider, Stefan, Jad Khoury, Bernard Marie Lachal, and Pierre Hollmuller (2016). "Geo-Dependent Heat Demand Model of the Swiss Building Stock". In: *EXPANDING BOUNDARIES Systems Thinking in the Built Environment.* Sustainable Built Environment (SBE) Regional Conference. Ed. by Guillaume Habert and Arno Schlueter. Zurich, Switzerland: vdf Hochschulverlag AG, pp. 286–290. DOI: 10.3218/3774-6_46. URL: http://archive-ouverte.unige.ch/unige:84240.

Schüler, Nils, Giorgio Agugiaro, Sébastien Cajot, and François Maréchal (2018a). "Linking Interactive Optimization for Urban Planning with a Semantic 3D City Model". In: ISPRS Technical Commission IV Symposium 2018. Delft, The Netherlands. URL: https://infoscience.epfl.ch/record/255763.

Schüler, Nils and Sébastien Cajot (2018a). "A Planning Support System Using Interactive Optimization". In: *Urban Energy Systems for Low Carbon Cities.* Elsevier.

– (2018b). "Use of Interactive Optimization for the Planning of New and Existing Neighborhoods". In: *Urban Energy Systems for Low Carbon Cities.* Elsevier.

Schüler, Nils, Sébastien Cajot, Markus Peter, Jessen Page, and François Maréchal (2018b). "The Optimum Is Not the Goal: Capturing the Decision Space for the Planning of New Neighborhoods". In: *Frontiers in Built Environment* 3.76. ISSN: 2297-3362. DOI: 10.3389/fbuil.2017.00076. URL: https://www.frontiersin.org/articles/10.3389/fbuil.2017.00076/full.

Schüler, Nils, Alessio Mastrucci, Alexandre Bertrand, Jessen Page, and François Maréchal (2015). "Heat Demand Estimation for Different Building Types at Regional Scale Considering Building Parameters and Urban Topography". In: *Energy Procedia.* 6th International Building Physics Conference. Vol. 78. Torino, Italy: Elsevier, pp. 3403–3409. DOI: 10.1016/j.egypro.2015.11.758. URL: http://linkinghub.elsevier.com/retrieve/pii/S187661021502490X.

Schweizerischer Ingenieur- und Architektenverein (2011). *La Voie SIA Vers l'efficacité Énergétique.*

– (2015). *Données d'utilisation Des Locaux Pour l'énergie et Les Installations Du Bâtiment.*

Sefair, Jorge A., Adriana Molano, Andrés L. Medaglia, and Olga L. Sarmiento (2012). "Locating Neighborhood Parks with a Lexicographic Multiobjective Optimization Method". In: *Community-Based Operations Research.* Ed. by Michael P. Johnson. Vol. 167. New York, NY: Springer New York, pp. 143–171. ISBN: 978-1-4614-0805-5 978-1-4614-0806-2. DOI: 10.1007/978-1-4614-0806-2_6. URL: http://link.springer.com/10.1007/978-1-4614-0806-2_6.

Sethi, Suresh and Gerhard Sorger (1991). "A Theory of Rolling Horizon Decision Making". In: *Annals of Operations Research* 29.1, pp. 387–415. URL: http://link.springer.com/article/10.1007/BF02283607.

Seto, Karen C., Burak Güneralp, and Lucy R. Hutyra (2012). "Global Forecasts of Urban Expansion to 2030 and Direct Impacts on Biodiversity and Carbon Pools". In: *Proceedings of the National Academy of Sciences* 109.40, pp. 16083–16088. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.1211658109. pmid: 22988086. URL: http://www.pnas.org/content/109/40/16083.

Shannon, Claude E. and Warren Weaver (1949). *The Mathematical Theory of Communication*. Urbana, IL: University of Illinois Press.

Shao, Min, Xiaoyan Tang, Yuanhang Zhang, and Wenjun Li (2006). "City Clusters in China: Air and Surface Water Pollution". In: *Frontiers in Ecology and the Environment* 4.7, pp. 353–361. ISSN: 1540-9309. DOI: 10.1890/1540-9295(2006)004[0353:CCICAA]2.0.CO;2. URL: https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/1540-9295%282006%29004%5B0353%3ACCICAA%5D2.0.CO%3B2.

Shi, Zhongming, Jimeno A. Fonseca, and Arno Schlueter (2017). "A Review of Simulation-Based Urban Form Generation and Optimization for Energy-Driven Urban Design". In: *Building and Environment* 121, pp. 119–129. ISSN: 03601323. DOI: 10.1016/j.buildenv.2017.05.006. URL: http://linkinghub.elsevier.com/retrieve/pii/S0360132317301865.

Sindram, Maximilian and Thomas H. Kolbe (2014). "Modeling of Urban Planning Actions by Complex Transactions on Semantic 3D City Models". In: *Proceedings of the International Environmental Modelling and Software Society (iEMSs)*. URL: https://mediatum.ub.tum.de/doc/1224665/file.pdf.

SITG (1957). *Le Territoire Genevois à La Carte*. URL: http://ge.ch/sitg/.

Söderman, Jarmo and Frank Pettersson (2006). "Structural and Operational Optimisation of Distributed Energy Systems". In: *Applied Thermal Engineering*. Process Integration, modelling and optimisation for energy saving and pollution reduction - PRES 2004 26.13, pp. 1400–1408. ISSN: 1359-4311. DOI: 10.1016/j.applthermaleng.2005.05.034. URL: http://www.sciencedirect.com/science/article/pii/S1359431105002164.

Sperling, Karl, Frede Hvelplund, and Brian Vad Mathiesen (2011). "Centralisation and Decentralisation in Strategic Municipal Energy Planning in Denmark". In: *Energy Policy* 39.3, pp. 1338–1351. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2010.12.006. URL: http://www.sciencedirect.com/science/article/pii/S0301421510008876.

Swan, Lukas G. and V. Ismet Ugursal (2008). "A New Hybrid End-Use Energy and Emissions Model of the Canadian Housing Stock". In:

– (2009). "Modeling of End-Use Energy Consumption in the Residential Sector: A Review of Modeling Techniques". In: *Renewable and Sustainable Energy Reviews* 13.8, pp. 1819–1835. ISSN: 1364-0321. DOI: 10.1016/j.rser.2008.09.033. URL: http://www.sciencedirect.com/science/article/pii/S1364032108001949.

Synnefa, A., M. Santamouris, and H. Akbari (2007). "Estimating the Effect of Using Cool Coatings on Energy Loads and Thermal Comfort in Residential Buildings in Various Climatic Conditions". In: *Energy and Buildings* 39.11, pp. 1167–1174. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2007.01.004. URL: http://www.sciencedirect.com/science/article/pii/S0378778807000126.

Thalmann, Philippe (2010). “Grössere Dichte Rentiert Nicht Immer”. In: *Swiss Real Estate Journal* 2010.1, pp. 50–59.

Thompson, Steven K. (2012). *Sampling*. 3rd. Wiley series in probability and statistics. Wiley. 472 pp. ISBN: 978-0-470-40231-3. URL: http://www.wiley.com/WileyCDA/WileyTitle/productCd-0470402318.html.

Thunnissen, Daniel P. (2003). “Uncertainty Classification for the Design and Development of Complex Systems”. In: *3rd Annual Predictive Methods Conference*. URL: http://cmapspublic3.ihmc.us/rid=1MHBNWQ8R-244KMJK-16CW/Uncertainty%20Classification%20for%20the%20Design%20and%20Development%20of%20Complex%20Systems.pdf.pdf.

Trutnevyte, Evelina (2013). “EXPANSE Methodology for Evaluating the Economic Potential of Renewable Energy from an Energy Mix Perspective”. In: *Applied Energy* 111, pp. 593–601. ISSN: 03062619. DOI: 10.1016/j.apenergy.2013.04.083. URL: http://linkinghub.elsevier.com/retrieve/pii/S0306261913003875.

Turcotte, Martin (2011). “Commuting to Work: Results of the 2010 General Social Survey”. In: *Canadian Social Trends* 92 (August), pp. 25–36.

United Nations (2018). *World Urbanization Prospects: The 2018 Revision*. URL: https://esa.un.org/unpd/wup/DataQuery/.

Van den Brink, Linda, Jantien Stoter, and Sisi Zlatanova (2013). “UML-Based Approach to Developing a CityGML Application Domain Extension”. In: *Transactions in GIS* 17.6, pp. 920–942.

Van Goor, Ad R., Sander de Leeuw, and Ruud Grotenhuis (2013). “Assessing Complexity of Supply Chains: Evidence from Wholesalers”. In: *International Journal of Operations & Production Management* 33.8, pp. 960–980. ISSN: 0144-3577. DOI: 10.1108/IJOPM-07-2012-0258. URL: https://www.emeraldinsight.com/doi/full/10.1108/IJOPM-07-2012-0258.

Ville de Lancy (2013). *Plan directeur communal de Lancy*. Genève, Switzerland. URL: http://www.lancy.ch/habitants/territoire-domaine-public/plan-directeur-communal-0.

Voll, Philip (2014). *Automated Optimization-Based Synthesis of Distributed Energy Supply Systems*. 1st ed. Aachener Beiträge zur Technischen Thermodynamik 1. Aachen: Wissenschaftsverl. Mainz. 185 pp. ISBN: 978-3-86130-474-6.

Weber, Céline (2008). “Multi-Objective Design and Optimization of District Energy Systems Including Polygeneration Energy Conversion Technologies”. PhD thesis. Lausanne, Switzerland: EPFL. 210 pp. URL: https://infoscience.epfl.ch/record/114786/files/EPFL_TH4018.pdf.

Weber, Céline, James Keirstead, Nilay Shah, and Nouri Samsatli (2010). “Trade-Offs between Layout of Cities and Design of District Energy Systems”. In: *Proceedings of the 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. ECOS. Lausanne, Switzerland: Laboratoire d’Énergétique Industrielle (LENI), EPFL.

Weber, Céline and Nilay Shah (2011). "Optimisation Based Design of a District Energy System for an Eco-Town in the United Kingdom". In: *Energy* 36.2, pp. 1292–1308. ISSN: 03605442. DOI: 10.1016/j.energy.2010.11.014. URL: http://linkinghub.elsevier.com/retrieve/pii/S0360544210006407.

Williams, H. P. (2013). *Model Building in Mathematical Programming*. 5th ed. Hoboken, N.J: Wiley. 411 pp. ISBN: 978-1-118-44333-0.

Wolpert, David H. (2013). "Information Width: A Way for the Second Law to Increase Complexity". In: *Complexity and the Arrow of Time*. Cambridge University Press. ISBN: 978-1-107-02725-1.

Woyke, Elizabeth (2018). "A Smarter Smart City". In: *MIT Technology Review*. URL: https://www.technologyreview.com/s/610249/a-smarter-smart-city/.

Yao, Zhihang, Claus Nagel, Felix Kunde, György Hudra, Philipp Willkomm, Andreas Donaubauer, Thomas Adolphi, and Thomas H. Kolbe (2018). "3DCityDB - a 3D Geodatabase Solution for the Management, Analysis, and Visualization of Semantic 3D City Models Based on CityGML". In: *Open Geospatial Data, Software and Standards* 3, p. 5. ISSN: 2363-7501. DOI: 10.1186/s40965-018-0046-7. URL: https://doi.org/10.1186/s40965-018-0046-7.

Yokoyama, Ryohei, Yasushi Hasegawa, and Koichi Ito (2002). "A MILP Decomposition Approach to Large Scale Optimization in Structural Design of Energy Supply Systems". In: *Energy Conversion and Management* 43.6, pp. 771–790. URL: http://www.sciencedirect.com/science/article/pii/S0196890401000759.

Yu, Jia, Yun Chen, Jianping Wu, Rui Liu, Hui Xu, Dongjing Yao, and Jing Fu (2014). "Particle Swarm Optimization Based Spatial Location Allocation of Urban Parks—A Case Study in Baoshan District, Shanghai, China". In: *Agro-Geoinformatics (Agro-Geoinformatics 2014), Third International Conference On*. IEEE, pp. 1–6. URL: http://ieeexplore.ieee.org/abstract/document/6910575/.

Yuan, Zhou, Shi Tiemao, and Gao Chang (2011). "Multi-Objective Optimal Location Planning of Urban Parks". In: IEEE, pp. 918–921. ISBN: 978-1-4577-0320-1. DOI: 10.1109/ICECC.2011.6066364. URL: http://ieeexplore.ieee.org/document/6066364/.

Zukin, Sharon, Valerie Trujillo, Peter Frase, Danielle Jackson, Tim Recuber, and Abraham Walker (2009). "New Retail Capital and Neighborhood Change: Boutiques and Gentrification in New York City". In: *City & Community* 8.1, pp. 47–64. ISSN: 1540-6040. DOI: 10.1111/j.1540-6040.2009.01269.x. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1540-6040.2009.01269.x.

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Publications

Book chapters

2018 Nils Schüler, Sébastien Cajot: A planning support system using interactive optimization, In: Urban energy systems for low carbon cities, *Elsevier*, in production

2018 Nils Schüler, Sébastien Cajot: Use of interactive optimization for the planning of new and existing neighborhoods, In: Urban energy systems for low carbon cities, *Elsevier*, in production

2018 Sébastien Cajot, Nils Schüler: Urban energy system planning: overview and main challenges, In: Urban energy systems for low carbon cities, *Elsevier*, in production

Journal articles

2018 Sébastien Cajot, Nils Schüler, Markus Peter, Andreas Koch, François Maréchal: Interactive optimization with parallel coordinates: exploring multidimensional spaces for decision support, *Frontiers in ICT*, submitted

2018 Nils Schüler, Sébastien Cajot, Markus Peter, Jessen Page, François Maréchal: The Optimum Is Not the Goal: Capturing the Decision Space for the Planning of New Neighborhoods, *Frontiers in Built Environment* 3 (2018), pp. 1–22

2016 Alexandre Bertrand, Alessio Mastrucci, Nils Schüler, Riad Aggoune, François Maréchal: Characterisation of domestic hot water end-uses for integrated urban thermal energy assessment and optimisation, *Applied Energy* 186 (2015), pp. 152–166

2015 Samira Fazlollahi, Nils Schüler, François Maréchal: A solid thermal storage model for the optimization of buildings operation strategy, *Energy* 88 (2015), pp. 209–222

2014 Christian Brandt, Nils Schüler, Matthias Gaderer, Jens M. Kuckelkorn: Development of a thermal oil operated waste heat exchanger within the off-gas of an electric arc furnace at steel mills, *Journal of Applied Thermal Engineering* 66 (2014), pp. 335–345

Conference papers

2018 Nils Schüler, Giorgio Agugiaro, Sébastien Cajot, François Maréchal: Linking interactive optimization for urban planning with a semantic 3D city model, accepted, *ISPRS Technical Commission IV Symposium 2018*, Delft, The Netherlands, October 2018

2017 Shanshan Hsieh, Nils Schüler, Zhongming Shi, Jimeno A. Fonseca, François Maréchal, Arno Schlueter: Defining density and land uses under energy performance targets at the early stage of urban planning processes, In: *Energy Procedia* 122, pp. 301-306, *CISBAT: Future Buildings & Districts - Energy Efficiency from Nano to Urban Scale*, Lausanne, Switzerland, September 2017

2017 Sébastien Cajot, Nils Schüler, Markus Peter, Andreas Koch, François Maréchal: Interactive optimization for the planning of urban systems, In: *Energy Procedia* 122, pp. 445-450, *CISBAT: Future Buildings & Districts - Energy Efficiency from Nano to Urban Scale*, Lausanne, Switzerland, September 2017

2016 Sébastien Cajot, Nils Schüler, Markus Peter, Andreas Koch, Jessen Page, François Maréchal: Establishing links for the planning of sustainable districts, In: *Expanding Boundaries: Systems Thinking in the Built Environment*, vdf Hochschulverlag AG, pp. 502–512, *SBE regional conference*, Zürich, Switzerland, June 2016

2015 Nils Schüler, Alessio Mastrucci, Alexandre Bertrand, Jessen Page, François Maréchal: Heat demand estimation for different building types at regional scale considering building parameters and urban topography, *Energy Procedia* 78, pp. 3403–3409, *IBPC*, Torino, Italy, June 2015

Education

Feb. 14 – Oct. 17 **Marie Curie Initial Training Network (ITN) "CI-NERGY"**, *European project on "Smart cities with sustainable energy systems"*, Several European insitutions and companies.

Oct. 06 – Sep. 09, Oct. 10 – Nov. 12 **Diploma in Mechanical Engineering**, *TU Munich*, Germany.
- fields of specialization: Sustainable Energy Systems, Numerical Mechanics

June 2005 **Abitur**, *Gymnasium Grafing*, Germany.

Diploma Thesis

Title *Optimization of a thermal oil-operated tube bundle heat exchanger within the off-gas of an electric arc furnace using CFD simulations*

Institution Bavarian Center for Applied Energy Research (ZAE Bayern), Prof. Spliethoff

Description Simulation of heat exchange and turbulent cross flow over a tube bank with fouling; optimization of geometry regarding heat transfer and resulting costs; modeling, meshing, pre- and postprocessing using Ansys CFX and Workbench

Second Term Paper

Title *Stacking sequence optimization in laminate material structure design*

Institution Institute of Lightweight Structures, TU Munich, Prof. Baier

Description Implementation of two different heuristic optimization algorithms (GA, DPSO) in Matlab; coupling of algorithms with structural analyses performed using Ansys APDL; examination and comparison of performance

First Term Paper

Title *Characterization of a syngas burner for the operation with hydrogen containing fuels*

Institution Institute for Thermodynamics, TU Munich, Prof. Sattelmayer

Description Experimental investigation of flame behavior in a swirl burner for varying fractions of hydrogen; physical integration of new components in test rig and their implementation in control system using LabVIEW

Computer Skills

varying levels of experience in:

Programming Lua, Python, VBA, Shell, C/C++

Mathematics AMPL, R, Matlab

Data PostgreSQL, CityGML, QGIS, Tableau, FME

Simulation Grashopper, Ansys, OpenFOAM, Simulink

Office MS Office, LaTeX

Languages

German	Native speaker	
English	Excellent command	*Common European Framework C1*
French	Very good command	*Common European Framework B2*
Spanish	Good communication skills	*Common European Framework A2*

Gap Year

Oct. 09 – Sep. 10 Traveling, climbing, and mountaineering in Asia, New Zealand, and South America