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A holistic model for analyzing energy benefits of urban density by relating energy use, building height, and overall city structure

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Abstract:
More than half of the world population live in cities, and the urban population is further expected to almost double within 2050. This opens a rare window of time for realizing energy savings through overall city planning. How the overall city structure influence energy consumption is, however, still poorly understood. A central theme in the sustainable development of urban form is the compact city, and as a key instrument of this densification, tall buildings may prove important. Yet, the overall energy-saving potential of building taller and denser remain largely unclear. Moreover, current studies are described as far from holistic, not capturing the interconnectedness and complexity of the system as a whole. They are mostly qualitative, and methods depend largely on context. There is thus a lack of a clear theoretical framework for understanding energy consumption at the urban scale. The ambition of this thesis is to address this knowledge gap.

This thesis develops a holistic optimization model for investigating the extent to which urban density and urban structure influence the energy consumption of the urban system. Energy aspects in land use planning, including the influence of building height, are addressed. The model relates energy costs of building heights of three stories and greater, with transportation and infrastructure energy benefits of building denser. Multiple scenarios of differing climate, population, and other variables have been simulated. Only factors considered to be correlated with urban density are taken into account. Of these, solar irradiation and the urban heat island effect have been left out due to their complex nature.

A denser and taller city structure than what is normal in cities today is found to be optimal for low urban energy use. The most influential urban density indicators are embodied energy (most heavily influenced by building lifetime) and floor area per capita. The findings of the research indicate that building heights approximately in the range 7-27 stories are optimal for a given population and building lifetime. For buildings taller than this the increased embodied energy outweighs further reduction potentials of other elements. Energy use per capita in a city with optimal density is increasing slightly with population. Transportation energy is generally found to be much less important than building energy, especially in dense small area scenarios, but becomes increasingly important for low-density scenarios with large urban areas. Road construction, elevator energy, and vertical water transportation energy does not significantly affect the overall energy budget. An energy saving potential for the urban metabolism of the investigated elements of approximately one third compared to a low-density scenario is found to be viable. However, energy savings of further densification in areas that already have high-density, close to the optimal, are not significant. The energy expenditure is significantly lower in the dense and tall scenarios - with implications for current and near-future city planning policies on optimizing land use based on city size. These findings improve the basis on which decisions are made for policy-makers and urban planners worldwide, although the significance of solar irradiation and the urban heat island effect should be investigated further. The model is a generalized theoretical abstraction and thus has its limitations. Further development of the model by including more elements as well as reducing uncertainties is needed. Nevertheless, the findings are relevant both for further development of existing cities and for conceptually planned future cities.

Keywords:
1. Urban density; building height; tall buildings
2. Theoretical urban energy modeling
3. Energy aspects in land use planning; sustainable cities
4. Embodied energy; transportation energy; heat loss energy; road infrastructure energy

A holistic model for analyzing energy benefits of urban density by relating energy use, building height, and overall city structure

Eirik Resch


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— Master Thesis —
Industrial Ecology Programme

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Contents

Preface

This master thesis was carried out with the goal of producing a scientific article for publication in an international peer-reviewed journal. The scientific paper is the core of the master thesis, and a central goal of the thesis was to prepare the paper for publication.

The following report provides supplementary material to the article, including the process of the thesis work, to reduce the gap between an article and a traditional thesis. The article in its original format is included in the last chapter.

The master thesis, equivalent to 30 ECTS, is carried out at the Department of Civil and Transport Engineering, Faculty of Engineering Science and Technology, Norwegian University of Science and Technology (NTNU), as a concluding work for the degree M.Sc. in Industrial Ecology at the same faculty.

I would like to thank my supervisor for supporting me throughout the last year of my studies, for his suggestions and encouragement, and for letting me be creative and pursue my own ideas and approaches in this research. A special thanks go to my family for supporting and helping me throughout my education, and for always believing in me. It would not have been the same without the endless knowledge and help from my father.

Abstract

More than half of the world population live in cities, and the urban population is further expected to almost double within 2050. This opens a rare window of time for realizing energy savings through overall city planning. How the overall city structure influence energy consumption is, however, still poorly understood. A central theme in the sustainable development of urban form is the compact city, and as a key instrument of this densification, tall buildings may prove important. Yet, the overall energy-saving potential of building taller and denser remain largely unclear. Moreover, current studies are described as far from holistic, not capturing the interconnectedness and complexity of the system as a whole. They are mostly qualitative, and methods depend largely on context. There is thus a lack of a clear theoretical framework for understanding energy consumption at the urban scale. The ambition of this thesis is to address this knowledge gap.

This thesis develops a holistic optimization model for investigating the extent to which urban density and urban structure influence the energy consumption of the urban system. Energy aspects in land use planning, including the influence of building height, are addressed. The model relates energy costs of building heights of three stories and greater, with transportation and infrastructure energy benefits of building denser. Multiple scenarios of differing climate, population, and other variables have been simulated. Only factors considered to be correlated with urban density are taken into account. Of these, solar irradiation and the urban heat island effect have been left out due to their complex nature.

A denser and taller city structure than what is normal in cities today is found to be optimal for low urban energy use. The most influential urban density indicators are embodied energy (most heavily influenced by building lifetime) and floor area per capita. The findings of the research indicate that building heights approximately in the range 7-27 stories are optimal for a given population and building lifetime. For buildings taller than this the increased embodied energy outweighs further reduction potentials of other elements. Energy use per capita in a city with optimal density is increasing slightly with population. Transportation energy is found to be much less important than building energy, especially in dense small area scenarios, but becomes increasingly important for low-density scenarios with large urban areas. Road construction, elevator energy, and vertical water transportation energy does not significantly affect the overall energy budget. An energy saving potential for the urban metabolism of the investigated elements of approximately one-third compared to a low-density scenario is found to be viable. However, energy savings of further densification in areas that already have high-density, close to the optimal, are not significant. The energy expenditure is significantly lower in the dense and tall scenarios - with implications for current and near-future city planning policies on optimizing land use based on city size. These findings improve the basis on which decisions are made for policy-makers and urban planners worldwide, although the significance of solar irradiation and the urban heat island effect should be investigated further. The model is a generalized theoretical abstraction and thus has its limitations. Further development of the model by including more elements as well as reducing uncertainties is needed. Nevertheless, the findings are relevant both for further development of existing cities and for conceptually planned future cities.

Sammendrag

Mer enn halvparten av verdens befolkning bor i byer, og den urbane befolkningen er videre ventet å nesten dobles innen 2050. Dette åpner et sjeldent tidsvindu for å realisere energibesparelser gjennom helhetlig byplanlegging. Det er imidlertid ingen god forståelse for hvordan den overordnede bystrukturen påvirker energiforbruket. Et sentralt tema innen bærekraftig utvikling av byer er den kompakte byformen, og som et sentralt virkemiddel til denne fortettingsprosessen kan høye bygninger være viktig. De overordnede mulighetene for energibesparelse ved å bygge høyere og tettere er fortsatt i stor grad uklart. Videre er dagens studier beskrevet som langt fra helhetlig, og kritiseres for å ikke ta hensyn til sammenkoblinger og kompleksiteten i systemet som helhet. Studiene er for det meste kvalitative, og metodiske fremgangsmåter avhenger i stor grad av konteksten. Det er således en mangel på et klart teoretisk rammeverk for å forstå energiforbruk på den urbane skala. Ambisjonen for denne tesen er å fylle dette kunnskapsgapet.

Denne avhandlingen utvikler en holistisk optimeringsmodell for å undersøke i hvilken grad bytetthet og bystruktur påvirker energiforbruket i det urbane systemet. Energiaspekter i arealplanlegging, herunder påvirkning av bygghøyde, er adressert. Modellen relaterer energikostnader av byggehøyder på tre etasjer og høyere, med transport- og infrastruktur energifordeler ved å bygge tettere. Flere scenarier med ulike klima, befolkninger, og andre variabler ble simulert. Kun faktorer som har energibruk korrelert med urban tetthet er tatt hensyn til. Av disse har solinnstråling og effekten av en urban varmeøy blitt utelatt på grunn av deres komplekse natur.

En tettere og høyere bystruktur enn det som er vanlig i dagens byer er funnet å være optimal for lavt energiforbruk. De mest innflytelsesrike indikatorene for optimal bytetthet er bundet energi i bygg (sterkt påvirket av byggets levetid) og gulvareal per innbygger. Resultatene av forskningen tyder på at byggehøyder i størrelsesorden 7-27 etasjer er optimalt for en gitt befolkning og bygg-levetid. For bygninger høyere enn dette vil den økte bundede energien overgå ytterligere reduksjonspotensialer fra andre byelementer. Energibruk per innbygger i en by med optimal tetthet øker med en større befolkning. Transportenergi er funnet å være mye mindre viktig enn energi relatert til bygg, særlig i tette og små

byer, men blir stadig viktigere for situasjoner med lav tetthet og store urbane områder. Energi relatert til veiinfrastruktur, heis, og vertikal vanntransport påvirker ikke det totale energibudsjettet i vesentlig grad. Et energibesparingspotensial på omtrent en tredjedel er funnet å være mulig for den urbane energimetabolismen til de elementer som ble undersøkt, sammenlignet med et scenario med lav tetthett. I områder som allerede har høy tetthet, nær det optimale, er en energibesparelse ved ytterligere fortetting ikke signifikant. Energiforbruket er betydelig lavere i tette og høye scenarier - med konsekvenser for nåværende og fremtidig byplanpolitikk som har som mål å optimalisere arealbruk basert på byens størrelse. Disse funnene bedrer beslutningsgrunnlaget for politikere og byplanleggere verden over, selv om betydningen av solinnstråling og varmeøyeffekten bør undersøkes nærmere. Modellen er en generalisert teoretisk abstraksjon og har dermed sine begrensninger. Videreutvikling av modellen ved å inkludere flere elementer samt redusere usikkerheter er nødvendig. Likevel er funnene relevante både for videreutvikling av eksisterende byer og for konseptuelt planlagte fremtidige byer.

1 Introduction

1.1 Importance of cities in the coming decades

With more than half of the world population already living in urban areas and an expected continued population growth in urban areas, making cities more sustainable is crucial to sustainable development. The fraction of urban population is dominating in many countries, often above eighty and in some cases more than ninety percent [1]. United Nations analysis and projection show that the world's rural population has already stopped growing and that population growth mainly takes place in cities. With an immense number of people moving from rural to urban areas, the projections show that we can expect 3 billion more urbanites within 2050. The result we can draw from this is that the majority of urban areas and infrastructure has yet to be built. This constitutes both challenges and opportunities for greenhouse gas (GHG) mitigation [2]. The Rio+20 United Nations Conference on Sustainable Development recognized both the needs of the urban poor to raise the quality of life and the need for sustainable cities as matters of great urgency for the United Nations development agenda [3; 4]. The way the world's cities are developed in the coming years will have a great impact on both those needs. In the 2015 Paris Agreement, 195 countries agreed to pursuit efforts to limit the increase in global average temperature to 1.5 °C above pre-industrial levels [5]. If this goal is to be achieved, the energy use in cities needs to be addressed. Cities are long lasting material stocks, once built they are hard to change and can maintain the same underlying structure for centuries. This limits what can and what cannot be changed easily. For example, it puts restrictions on moving patterns, and buildings are often built for a lifetime longer than the humans who are building them. The Intergovernmental Panel on Climate Change (IPCC) states:

> "The largest opportunities for future urban GHG emissions reduction might be in rapidly urbanizing countries where urban form and infrastructure patterns of land use, transport choice, housing, and behavior are not locked-in and where key mitigation strategies include co-locating high residential with high employment densities." [2]

Thus, finding an optimal city structure is of great interest both for the energy and environmental challenges currently facing the world and for the quality of the lives of billions of people.

1.2 Problem description, objectives and scope

There is a lack of a holistic model for urban energy use that captures the interactions of the many urban variables, as well as how this is related to compact urban form (as comes clear from literature in chapter 2.2). The aim of this master thesis is to bridge this knowledge gap, thus being able to isolate the most important variables and gain valuable new insight into the dynamics of the urban system. The possibility of an optimal building height and an optimal urban density that will minimize building- transportation- and infrastructure energy use is investigated. This is all analyzed for varying climates, populations, and other parameters. The scope of the work is a large-scale implementation of many urban elements. At the same time, the level of detail and the number of elements included is inevitably limited by the sheer complexity of the urban system and the fact that all methodologies are developed from scratch.

1.3 Master thesis as published scientific article

This master thesis is carried out with the goal of producing a scientific article to be published in an international peer-reviewed journal. Thus, the main product of the thesis is found in the attached article, which is submitted for publishing in the journal Elsevier Energy Procedia. Compact scientific writing is not well suited for all the traditional elements of a master thesis. The following report is a supplementary addition to the article, providing more in-depth explanatory material both on the work presented in the article and on the process performed and choices made. The article can be read independently of this report, either before or after. As the article is the main product and is an independent, self-contained paper, this supplementary material is kept short and concise.

1.4 Authors' contribution

The work was carried out under the supervision of Associate Professor Rolf André Bohne, and co-supervisor Professor Trond Kvamsdal. Rolf André Bohne provided thoughts on general system definition and on presenting the results. Trond Kvamsdal supervised during the project thesis that led up to the master thesis, but not during the master thesis itself. All work presented is original work solely of the undersigned, Eirik Resch; including system definitions, development of methodologies, presentation of results, and writing of the article.

The writing of the article was aided by Jardar Lohne, who provided advice on scientific writing and some feedback on layout and written formulations. Besides from some feedback by Jardar Lohne and Rolf André Bohne, the article was written solely by the undersigned, Eirik Resch; including text, the design of figures and illustrations, and editorial design. The layout is in accordance with standards for the journal in question.

1.5 Outline of thesis

The *Theory* section gives an introduction to the topic and the current state of the art. The *Methodology* describes the process of working out a methodology, and explains how the density related energy use was modeled as well as why these choices have been made. Explanations given in the paper will here only be briefly summarized, while elements and computations not elaborated on in the paper will be more thoroughly explained. *Model limitations* are then addressed. A *Results* section with the main findings of the master thesis follows. The *Conclusion and policy implications* section concludes the thesis and its implications, while the *Further research* section suggests and recommends how the work may be continued. Finally, the *Paper* section presents the scientific article in its original format.

2 Theory

2.1 Sustainability of cities

A city is a complex system serving a wide range of purposes. Most notably, cities gather economic, productive, and social activities [6]. Supporting these purposes requires energy, which in turn produce CO_2 emissions, as well as other pollutants affecting both the climate and the health of human beings. Also, energy is a scarce resource and thus reducing energy use is a goal in itself.

A lot of work has been done to make cities more sustainable by taking specific actions, like making buildings and transportation more energy efficient, reuse of materials and energy, and implementation of renewable energy [7]. However, very little of this research has focused on the overall structure of cities; the urban dimension as a system of energy consumption attracts much less attention than its individual components [8].

The vast majority of urban areas developed due to historical reasons; often by a chain of coincidences. Taking into account the enormous potential for energy savings in overall city planning, the lack of focus on energy in urban planning may be a major mistake. One of the key characteristics of urban areas is the height of buildings. The role of building heights in this context is however poorly understood, although it may be a significant determinant both on urban density and on factors affecting the quality of life of the urban dwellers.

Compact urban form is identified by the IPCC as an important sectoral mitigation measure [9]. Several reports on world energy use show that cities consume up to 75% of global energy and account for 78% of anthropogenic carbon emissions [10; 11]. The need for addressing and understanding environmental and energy issues of urban areas is therefore widely acknowledged, and if cities are part of the problem, they must inevitably also be part of the solution [8]. How urban structure in the form of density and building height influences energy use and pollution should be investigated further through a holistic approach to urban form. In fact, “spatial planning competencies and political will to support integrated land-use and transportation planning”, was recognized by IPCC’s technical experts on urban environment as one out of four key factors of climate policy

[2].

To understand urban energy consumption, it can be helpful to take the point of view that cities have their own metabolic system, and like any thermodynamic system, it can be either efficient or inefficient [12]. To understand the dynamics of such a complex system, it must be broken down into smaller elements. One such breakdown is between direct and indirect energy use. This can be done with Life Cycle Analysis (LCA), which is a method for assessing the total environmental impacts of a product or service, from the extraction of raw materials, and all processes leading up to the final product being used, its operational use-phase, and then demolished or handled at its end-of-life. A detailed breakdown of the processes can give insight as to which processes are most influential. The impacts can be measured by many different indicators, of which a commonly used indicator is Global Warming Potential (GWP). GWP is a measure of the total warming potential (heat absorption) over a certain time, of all greenhouse gas emissions caused by the product or service, relative to the corresponding warming potential of CO_2. Similarly, Life Cycle Energy Analysis (LCEA) is assessing the total energy use due to that product or service, over its entire life cycle. Embodied energy is the energy that is not due to direct use (operation), but rather the energy used in the pre- and post-use phases, as well as for maintenance. These indirect processes responsible for the energy embodied in the urban infrastructure, including buildings, take up a significant proportion of the overall energy use. Including it in a holistic model thus becomes crucial. On the other side of the coin is the operational energy use. Trends of operational (i.e. direct) energy use in cities can be split into the two following groups of cities (neglecting the industry sector) [12]:

The first group is wealthier cities in the industrialized world, where most operational energy is used to heat and light residential and commercial buildings, and transport follow as the second greatest consumer of energy.

The second group is cities such as Mexico City, Hong Kong and Cape Town, where transport is the largest consumer of operational energy followed by residential and commercial buildings.

In the large cities of slower growing economy countries, the transport sector consumes more than half of the total energy used [12]. Cities are in many cases more sustainable than less dense areas, but they also bring with them it the challenge of growing unsustainable suburbs due to area scarcity. More compact cities can deal with this problem by housing more people inside the city, thus avoiding the growth of suburbs. Co-benefits of compact cities may include better handling of scarcity of area and resources, reducing commuting time, making way for more affordable living, more green areas can improve the quality of life of its residents. Sharing of resources, both human, technological and natural, can give scale benefits. It is generally considered that there are reduced transport costs both for goods, people, and ideas (information). Also, eco-impacts are concentrated to a smaller area, leaving a larger portion of nature untouched. These co-benefits are not inevitably going to occur in every compact city, but can be achieved in a compact city where the right measures have been taken.

2.2 State of the art and the need for a holistic approach to energy use in cities

The study of how the built environment is related to energy consumption started to gain momentum after the energy crisis in the 70's when petroleum shortages and elevated energy prices in the western world sparked the interest [13; 14]. However, how the physical and functional organization of cities and energy consumption affect energy consumption are being studied only recently. A recent literature review of the research done on this topic has been conducted by Papa, Gargiulo and Zucaro [8]. The current scientific literature in the field is divided into two branches by the authors.

The first branch are studies related to urban morphology, i.e. relationships between urban density, transport, and energy consumption. A distinction between the compact city and urban sprawl as the two main settlement models is made. There is a consensus that compact form can influence both energy consumption and energy consumption per capita. One study shows that there is an inverse relationship between transport energy consumption and density of population. High-density cities such as Hong Kong and the core area of New York are also the most efficient energy consumers. In contrast, low-density cities such as those in North America consume more energy per capita [15]. The main reason for this difference in energy use is that low-density cities have highly dispersed activity and have a heavy dependence on private transport. Still, at particular high-density Owen (1986) [14] argues that "energy consumption benefits may begin to be outweighed by the side benefits arising from congestion". Another effect is that in urban sprawl the most influential variable is the size of the dwellings per capita. This lower occupancy requires more energy for heating, cooling, and so on, as demonstrated by different comparison studies [16; 17; 18; 19].

The second branch are studies related to solar gains and heat loss of the urban environment, investigating the influence of environmental and microclimatic variables. Such variables include the barrier effect to solar radiation, which is relating proximity of buildings with passive solar heating, the possibility of utilizing renewable photovoltaic energy and the urban heat island effect, which is the empirical fact that temperatures are higher in urban areas than in neighboring ones. A compact urban form can accelerate the urban heat island effect, and by doing so minimize heat loss. At the same time, solar accessibility and potential for photovoltaic and passive heating energy decrease [20]. Green areas can also have a positive effect on the microclimate. Various scholars have found that a greater presence of green areas will result in reduced energy consumption and CO2 emissions. Trees increase natural ventilation and cool down air through evapotranspiration, which helps cooling down buildings in the summer. Trees can also produce a barrier against wind, and prevent cooling in the winter [21; 22].

These studies are not only divided into these groups, but focus only on one or a few urban elements at a time. However, the urban energy system is highly non-linear, and overall results and prioritization are likely to change significantly in a holistic approach that takes interactions between the elements into account. The same literature study identifies the set of physical and environmental variables from literature that most affect energy consumption at the urban scale. The density-related variables with high incidence on energy consumption are urban horizon angle (relating to the sky-view obstruction angle), aspect ratio (building height/width), territorial density, population density, green area density, surface/volume ratio, and building floor area. (Building function, building orientation, and public transportation density are also among the most influential, but are not directly related to urban density.) However, the authors warn that the incidence of these variables can only be set qualitatively, as the effects of internal interaction between these variables, and with the urban form and geometry are heavily understudied and controversial. Most of these variables are either explicitly or implicitly investigated in this thesis, along with additional variables that previously have not been, and interactions between them are thoroughly investigated.

One noteworthy effort at quantitatively modeling the complex urban system; the currently most comprehensive framework existing, is the open-source project UrbanSim. It is a scenario planning tool that has been continuously refined over the last two decades, and according to the developers, it is the most used and cited model system for urban planning [23]. It is mainly simulating metropolitan real estate markets and impacts of land use and transportation plans, and it does so on a very detailed level. The software is case-based, meaning a large amount of input data is needed on the urban area under investigation, and that scenario results are valid for the specific case only. Future scenarios are modeled to explore the effects of infrastructure and policy choices on accessibility (motorized and non-motorized), housing prices, greenhouse gas emissions, and open space and environmentally sensitive habitats [24]. Although UrbanSim is incorporating the interactions between land use, transportation, buildings, the economy, and the environment, it does so on a highly detailed case-specific level, and hardly tells much about universal artifacts of the urban system. The modeling of energy flow is not the main goal, and building energy is not generally implemented. Neither does it allow for sensitivity analysis of the many urban parameters in a practical manner, as to explore which urban indicators are most influential on energy use. Thus, it is not a model intended for extracting generally applicable prediction patterns on urban energy use.

The main findings from the literature study conducted by Papa, Gargiulo and Zucaro [8] is the absence of a clear theoretical framework for understanding energy consumption at the urban scale. Current studies are described as far from holistic, not capturing the interconnectedness and complexity of the system as a whole. They are mostly qualitative, and methods depend largely on context. One example is that the urban density at northern latitudes affects solar accessibility more than in equatorial latitudes [25; 26]. Also, the conclusions of current research are described as possibly uncertain and opposite because they do not take into account the diversity of variables existent in the nature of cities. A more holistic, though not complete, approach to a theoretical framework is attempted in this paper.

3 Methodology

3.1 Choosing methodology

The multi-dimensional nature of the urban energy issue, combined with the interconnectedness of its elements makes many approaches to the problem possible. Initially, Mathematical Optimization from the field of Operations Research was chosen as a fit choice for analyzing this problem. During the process this method was found to be extremely computationally demanding, on the verge to being infeasible for the current problem. Additionally, this method was in many ways a computational black box that allowed for little insight into the processes involved. As further exploration and validation of the internal processes were desirable, during the work with the master thesis, a change of methodology was undertaken. Parametric modeling was found to be a more fit choice for analyzing the problem. Moduled numerical calculations allowed for more freedom both in defining the system and in analyzing it. By investigating the relative importance of the different parameters and variables, a deeper understanding of the model can be reached, allowing for a more thorough analysis and explanation of the results. Their relative importance is determined through a global sensitivity analysis, that not only assess the direct effects of the given parameter but also includes its indirect effects through its interconnectedness with all the remaining parameters.

Initially, the exact physical placement of elements in a city grid was one of the main outputs of the calculations, and how the individual parameters influenced the outputs was information partially hidden in the model. Later it was decided that the general abstracted structure of the city, with a more detailed breakdown of energy use, is what is of real interest. In that way, the results become more universally applicable and thus more relevant. It also allows for a more thorough model calibration and validation. The exact placement of urban elements is of less interest in a holistic model as such and was omitted in favor of more universal findings.

The process of choosing methodology was characterized by trial and error, followed by changing or improving the methods in an iterative manner. Learning new software along the way was necessary. As neither the problem nor the approach to the problem was defined from the beginning, working out a suitable methodology was an essential part of the work. The final methodology settled upon was found through many iterative refinements and was a contiunuos process, resulting in original methodological work.

3.2 System analysis

The urban system was analyzed through a systems thinking approach, looking at the system as a whole as opposed to its individual elements only. The system was broken down into its most fundamental elements and from here an abstracted urban model was synthesized. Looking at individual components only will at best provide an insufficient understanding, and may lead to false prioritizations in energy policies. It was therefore considered important to compare all urban energy components related to density on an equal basis, determine which of these are the most influential components and then model them in a holistic framework. As energy use related to urban density is the focus of this study, only elements considered to be influenced by density are included as model components. These components; transportation, buildings, and recreational area; need (i) an input of energy, and/or (ii) an area in the urban landscape. Both energy use and land use change as density changes. The components were then split further, with a special focus on buildings and how energy use is affected by height. Only the components considered most influential were included in the model, while the rest were omitted for the sake of simplicity of the model. Other components were omitted due to the complexity of their effects, most notably the effects of the urban heat island and solar irradiation. A complex structure such as a city has a great number of possible configurations, of which many of the factors are interconnected in terms of their contribution to energy use. These individual components are subject to a range of requirements, i.e. constraints, necessary for satisfying their individual goals set by humans. These requirements should be met in the most efficient way, with the overall goal of minimizing the energy use, thus optimizing the energy performance of the city.

Some urban elements encourage compactness of city structure and thus building tall, to lessen heat loss and decrease transportation distances and the need for infrastructure, while others limit the benefit of building tall due to the increased embodied energy needed for extra stories.

3.3 Initial approach through mathematical optimization

In the scientific field of Operations Research, Mathematical Programming describes the mathematical modeling of a given optimization problem. This model aims to find the optimal solution under a set of given circumstances. First, key variables that influence the quality of decisions are selected and related in what is called *the objective function.* Secondly, a set of *constraints* are defined. This model is then algorithmically solved by a computer to attain a good feasible solution, or ultimately, if possible, the *globally best* solution in the context of the model formulation. For a program with nonlinear objective function and nonlinear constraints, this is very often not feasible, and one must work with *locally optimal* solutions instead [27].

A general formulation for mixed integer (binary) nonlinear minimization program used in this paper takes the form

$$\min z = \sum_i f(X_i, \delta_i) \tag{1}$$

$$\text{subject to } g_k(X_i, \delta_j) \leq b_k, \forall k \tag{2}$$

$$X_i \geq 0, \forall i \tag{3}$$

$$\delta_j \ binary \ \forall j \tag{4}$$

where z is the objective function, X_i is a vector of the non-negative decision variables, δ_j is a vector of the binary decision variables, and the subsequent g_k equations are the constraints that are to be satisfied. Solving such a problem requires a significant amount of computational power and should therefore be simplified as much as possible, without omitting important features of the physical system.

In this approach to modeling the urban system, the physical placement of buildings and public areas, as well as public transportation nodes, was a central part of the calculations. As such, the results displayed a city grid with a specific placement of each element. The city was divided into a Cartesian grid of enumerated cells from the set i and j, each representing all cells. The reason for having two sets representing the same cells was to be able to compare them with each other two at a time. The enumeration begins at the center and spirals outwards in the anticlockwise direction as visualized in figure 1a. This way the model can easily be scaled for each run both by the modeler and by the solver. Each cell with a resolution of 140 meters, equally wide and long, resulting in an area of 19600 square meters per cell that can serve one out of four purposes:

1. a residential area providing housing
2. a commercial area containing most of the workplaces of the population
3. a public transportation node
4. a public open space

The first two of these, residential cells and commercial cells, were the ones chosen for further investigation in terms of energy use as a consequence of building height, while the latter two are static in the sense that they consume a specific amount of energy per cell. The dimensions and layout of residential and commercial cells are outlined in figure 1b.

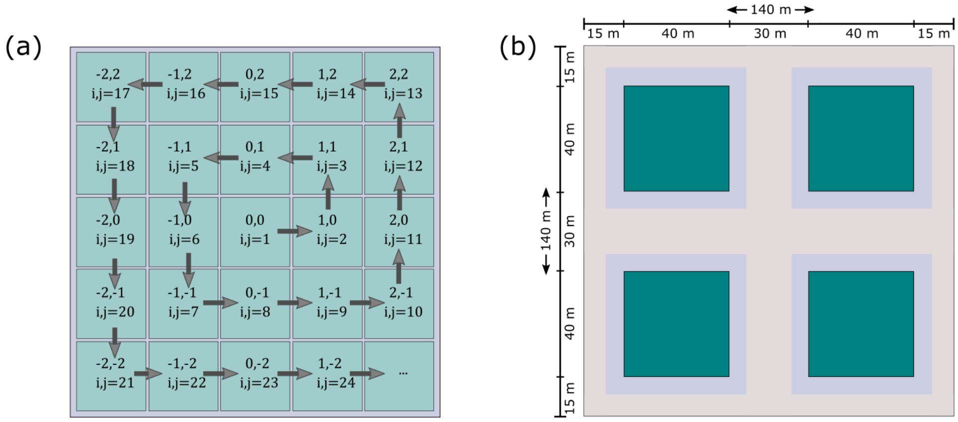

Figure 1: (a) Coordinates and enumeration of cells in the mathematical optimization approach. Enumeration beginning at the origin and spiraling outwards in the anticlockwise direction. (b) Dimensions and layout of residential and commercial cells. Each cell has four buildings (green) surrounded by sidewalks (grey) and streets (brown).

Under a range of mathematical constraints, a commercial solver capable of solving nonlinear binary mixed-integer problems was applied. Preliminary results are shown in figure 2 and 3. The results show that for these building heights, of the urban elements included in this study, embodied energy in buildings have the most influence on the energy of the urban system. Heat loss to the environment, elevator operational energy, and water transportation energy are of less importance. Transportation energy, as well as road construction, are found to play a very small role, which is likely due to the small distances and compactness of the modeled city.

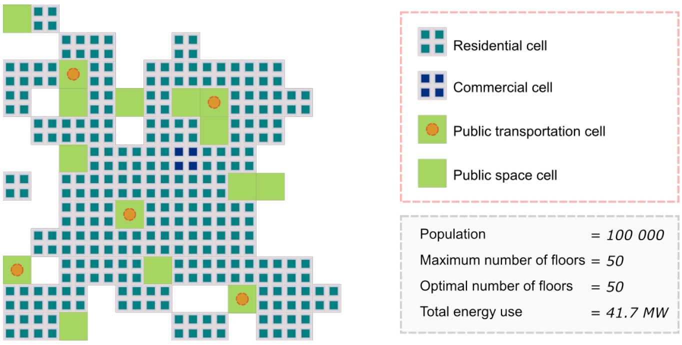

Figure 2: Results from mathematical optimization approach. Resulting city grid structure when the maximum number of stories allowed was set to 50.

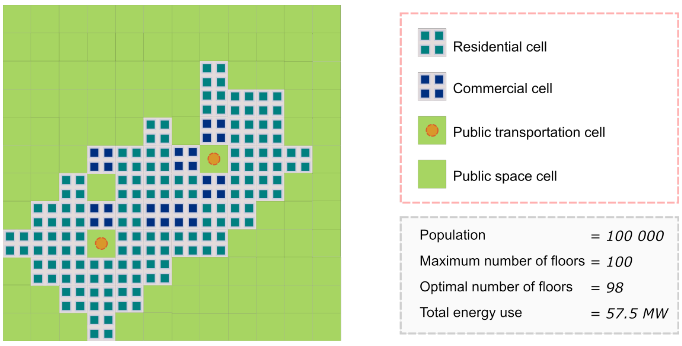

Figure 3: Results from mathematical optimization approach. Resulting city grid structure when the maximum number of stories allowed was set to 100.

A simulation with building heights of 50 stories was found to be more energy efficient than 98 stories. Embodied energy, elevator energy and water energy are roughly cut in half, while heat loss is doubled.

The resulting city shape deviates from the circular shape one would expect when the distances are minimized. This is likely because solutions are only locally optimal and that better solutions exist. Finding a solution closer to the globally optimal solution of the system requires a lot of computational power. An effort was made to simplify computations, but ultimately the mathematical optimization approach was omitted in favor of parametric modeling.

3.4 Final approach through parametric modeling

3.4.1 System definition and model assumptions

A mathematical model for investigating how the numerous parameters that determine urban density influence energy use in cities was developed. The parameters investigated include design-, societal- and technological- parameters, which are shown as inputs in figure 4. The procedure outlined in the figure runs for all stories from 3 to 60 and an optimum is determined. This is done for all combinations of input parameters, which allows for an assessment of which indicators (parameters) are of highest importance.

Four urban elements are included in the model: transportation energy, road infrastructure energy, initial embodied energy, and heating energy. The calculations are fundamentally based on the number of buildings needed for a given set of input parameters; this is calculated for all building heights. The number of buildings both determine the size of the urban area and influence total energy use of buildings. The area of the city is calculated based on four spatial parameters as well as population and is used to calculate transportation and road infrastructure energy. Building energy of an individual building is not directly dependent on area, but as the number of buildings increases, the larger area is increasing transportation energy and therefore encouraging taller buildings.

A simplified description of the model with the most important equations follows. A less mathematical description with more detailed explanations on the choices made can be found in the paper in chapter 8.

3.4.2 Modeling urban area

The number of buildings needed $N_{buildings}(s)$ for a given number of stories s is

$$N_{buildings}(s) = \frac{P \cdot FAPC}{0.85 \cdot W^2 \cdot s}, \tag{5}$$

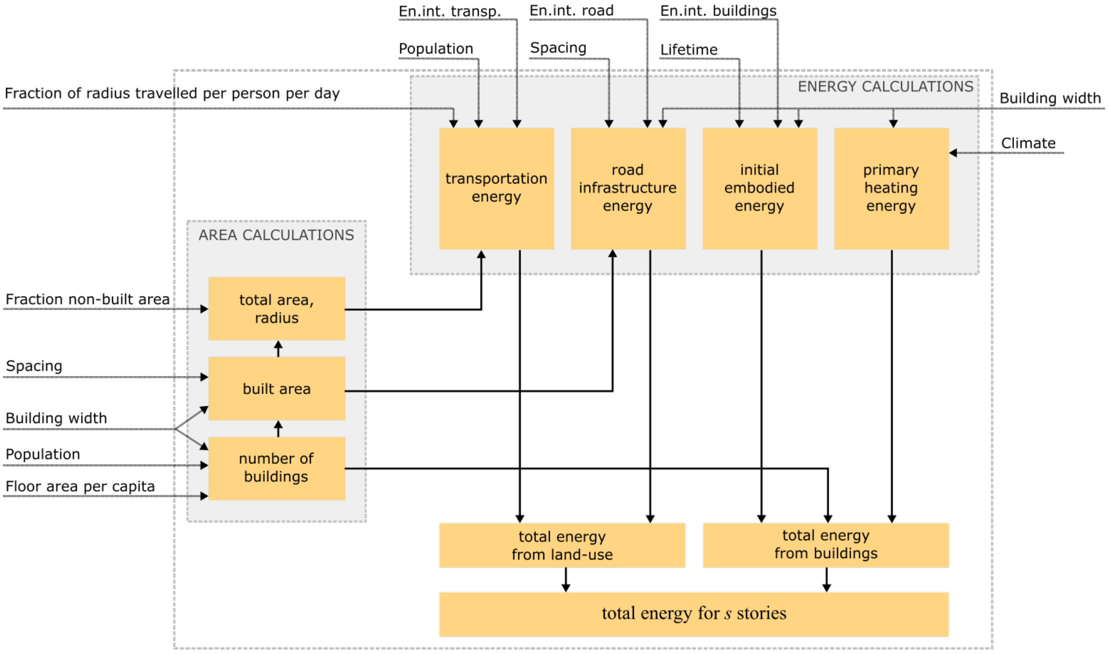

Figure 4: Conceptual mathematical model for calculation of city energy for s stories. This procedure is run for all stories from 3 to 60 and an optimum is determined for all combinations of input parameters.

and varies with population P, floor area per capita $FAPC$, and the usable story space per story, which is 85% of the building footprint. The building footprint is the square of the building width W. The built area A_{built} is the product of the number of buildings and the area plot of the building and its surrounding area, as in eq. (6). This area plot is determined by the building footprint and distance to neighbouring buildings, i.e spacing S.

$$A_{built}(s) = N_{buildings}(s) \cdot (W + S)^2 \tag{6}$$

The total urban area A_{total} is the built area plus a proportion of non-built area. The non-built area $f_{non-built}$ is the fraction of the total area A_{total} which is non-built. A_{total} is calulated as follows

$$A_{total}(s) = \frac{A_{built}(s)}{1 - f_{non-built}}. \tag{7}$$

The urban area is assumed to be a circular disc. A circular city shape is minimizing all relative distances and can therefore be a seen as an optimal shape. The radius is simply calculated from the total area,

$$r(s) = \sqrt{A_{total}(s)/\pi}. \tag{8}$$

3.4.3 Modeling embodied energy

The initial embodied energy of buildings $E_{embodied}(s)$ as a funtion of stories s is calculated as follows

$$E_{embodied}(s) = W^2 \cdot (as^2 + bs)/L, \tag{9}$$

where the coefficients a and b are calculated parameter values, and $as + b$ is the initial embodied energy per m^2 Gross Floor Area in a building of s stories. These coefficients are found through linear regression of 68 Life Cycle Analyses from literaure [28; 29; 30; 31; 32] where both number of stories and total floor area are described. The regression and confidence interval is shown in figure 5. Details on the parameter estimation are found in the article.

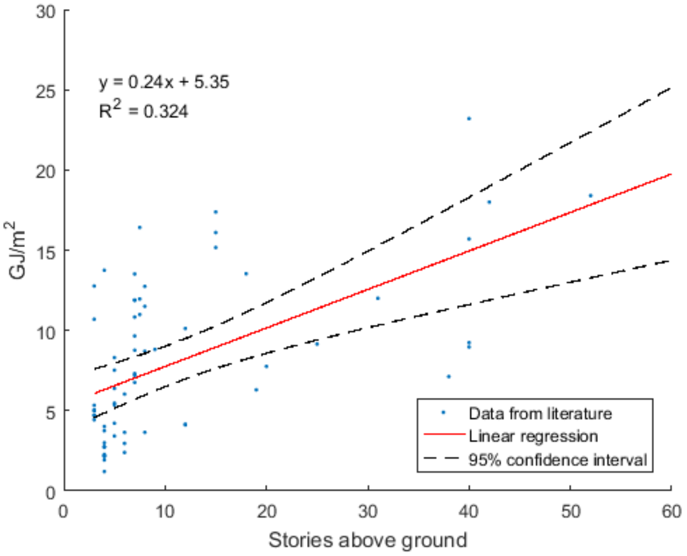

Figure 5: Initial embodied energy (primary) as a funciton of above ground story count.

3.4.4 Modeling heating energy

The primary energy needed for space heating and ventilation (as a consequence of heat loss) of an arbitrary building was modeled using the methodology for energy calculation applied in the European research project TABULA [33] as a basis. TABULA has a generalized set of calculations that are equally applied by all participating countries. Using this method as a basis, as well as representative example buildings from that project makes it possible to calibrate and validate the energy calculations. The method was expanded and generalized such that the number of stories can be varied.

Heat loss parameter values are used from the four example buildings from TABULA [33] with building codes in table 1. These buildings are representative of the climate and building technology of that country and are the basis for the inclusion of climate as a variable. In addition to a variation with climate, the heating need per floor area changes with building height, as a result of the change in envelope area per floor area. Thus, the envelope area calculations are essential to derive the heating energy as a function of building height.

The area of the roof $A_{env,r}$ is the same as the building footprint $A_{env,g}$,

$$A_{env,r} = A_{env,g} = W^2, \tag{10}$$

and the area of the four walls, including windows, as a function of stories s is

$$A_{env,wa,wi}(s) = 4 \cdot W \cdot h_{story}(s) \cdot s, \tag{11}$$

where W is the building width and s is the number of stories. h_{story} is the ceiling to ceiling height, which is 3.4 m/story [34] for stories ranging from 3 to 30. For buildings with more than 30 stories, the empirically based formula $7.75s^{-1} + 3.15$ m/story from [35] is applied. Of the total wall and window area $A_{env,wa,wi}$, 20% is window and 80% is wall. This ratio is an approximation that was extracted from the tabula data.

The conditioned floor area per building $A_C(s)$ (used in the calculation of ventilation heat loss), is the building footprint minus 20 cm thick walls, times the number of stories s

$$A_C(s) = (W - 0.4)^2 \cdot s. \tag{12}$$

The energy need for heating $Q(s)$ in a building of s stories is

$$Q(s) = [Q_{ht}(s) - \eta_{h,gn} \cdot Q_{int}(s)] \frac{\alpha}{\beta_c}, \tag{13}$$

where Q_{ht} is the energy lost by heat transfer to the environment, Q_{int} is the energy gained from internal heat sources, $\eta_{h,gn}$ is the gain utilisation factor for heating, α is the delivered to primary energy conversion factor, and β_c is the adjustment factor applied to calibrate the calculated energy with the energy given in TABULA for the chosen example building in country c. The delivered to primary energy conversion factor α is the average tabula value for the four buildings, 1.237. The calibration factors β_c are given in table 1.

The average heat transfer energy $Q_{ht}(s)$ in a building with s stories is calculated as

$$Q_{ht}(s) = [H_{tr}(s) + H_{ve}(s)] \cdot F_{red} \cdot (T_{in} - T_{ex}) \cdot d_h, \tag{14}$$

where H_{tr} and H_{ve} are the heat transfer coefficients by transmission and ventilation, F_{red} is the temperature reduction factor, T_{in} and T_{in} is the internal and external temperatures of the building, d_h is the number of yearly heating days.

The heat transfer coefficient by transmission H_{tr} is the sum of the heat transfer coefficients of the roof $H_{tr,r}$, wall $H_{tr,wa}$, ground $H_{tr,g}$, windows $H_{tr,wi}$, and thermal bridging $H_{tr,tb}$. Calculations for these heat transfer coefficients as a function of stories s are shown in eq. (15).

$$\begin{aligned} H_{tr,i}(s) &= U_{actual,i} \cdot A_{env,i}(s) \cdot b_{tr,i}, \qquad i = r, wa, g, wi \\ H_{tb}(s) &= U_{tb} \cdot b_{tr,tb} \sum A_{env,i}(s), \end{aligned} \tag{15}$$

where $U_{actual,i}$ is the actual U-value, $A_{env,i}$ is the external area dimensions, and $b_{tr,i}$ is the soil adjustment factor.

The heat transfer coefficient by ventilation $H_{ve}(s)$ as a function of stories s is calculated as

$$H_{ve}(s) = c_{p,air}(n_{air,use} + n_{air,infiltration})A_C(s) \cdot h_{room}, \tag{16}$$

where $c_{p,air}$ is the volume-specific heat capacity of air, $n_{air,use}$ and $n_{air,infiltration}$ are the air change rates by use and by infiltration, A_C is the conditioned floor area, and h_{room} is the interior room height.

The heat gain from internal heat sources $Q_{int}(s)$ is calculated as

$$Q_{int}(s) = \phi \cdot d_h \cdot A_C(s), \tag{17}$$

where ϕ is internal heat sources (W/m^2).

Table 1: The four TABULA buildings used in the heating energy calculations.

Country (*climate zone*)	β	TABULA building code [33]
Norway (*national*)	1.0709	NO.N.AB.07.Gen.ReEx.001.001
Belgium (*national*)	1.1097	BE.N.AB.06.Gen.ReEx.001.001
France (*national*)	1.0891	FR.N.AB.10.Gen.ReEx.001.001
Spain (*Mediterranean*)	0.6492	ES.ME.AB.06.Gen.ReEx.001.001

3.4.5 Modeling transportation energy

Transportation energy was modeled based on the city radius, using two different approaches. One approach uses a dynamic modal share that varies with urban density, and the other has a static modal share. The total inner-city transportation energy $E_{transportation}(s)$ as a function of stories s is in both cases calculated as

$$E_{transportation}(s) = I_{transportation} \cdot f_{radius} \cdot r(s) \cdot P, \tag{18}$$

where $I_{transportation}$ is the energy intensity per-person-and-meter, f_{radius} is the fraction of the radius traveled daily on a per-person average, r is the radius and P is the population. Data for the per-person-and-meter energy intensity $I_{transportation}$ is based on modal share data from 23 of the world's large cities [36], as well as the energy intensity of cars, I_{car}, busses, I_{bus}, and rail, I_{rail} from Japan [37], which has a large and effective public transportation system. The energy intensity of walking and cycling $I_{walking/cycling}$ is zero. Both approaches use the same modal share data, but the calculations are different.

The static approach use average modal share values, ms, for the 23 cities, and a weighted average is calculated as follows

$$I_{transportation} = ms_{car} \cdot I_{car} + ms_{public} \cdot \tfrac{1}{2}(I_{bus} + I_{rail}) + ms_{walk/bycycle} \cdot I_{walk/bycycle} \tag{19}$$

The dynamic approach has an energy intensity that varies with urban density (defined as inhabitants per total area). A power function regression was made based on the available data, shown in figure 6. There is a clear trend of reduced private transportation share with higher densities. The remaining share between public transportation and walking/cycling is varying. All the available data is in the lower bound of the densities achieved through this model, so a saturation point is assumed with a low private transportation share, and a

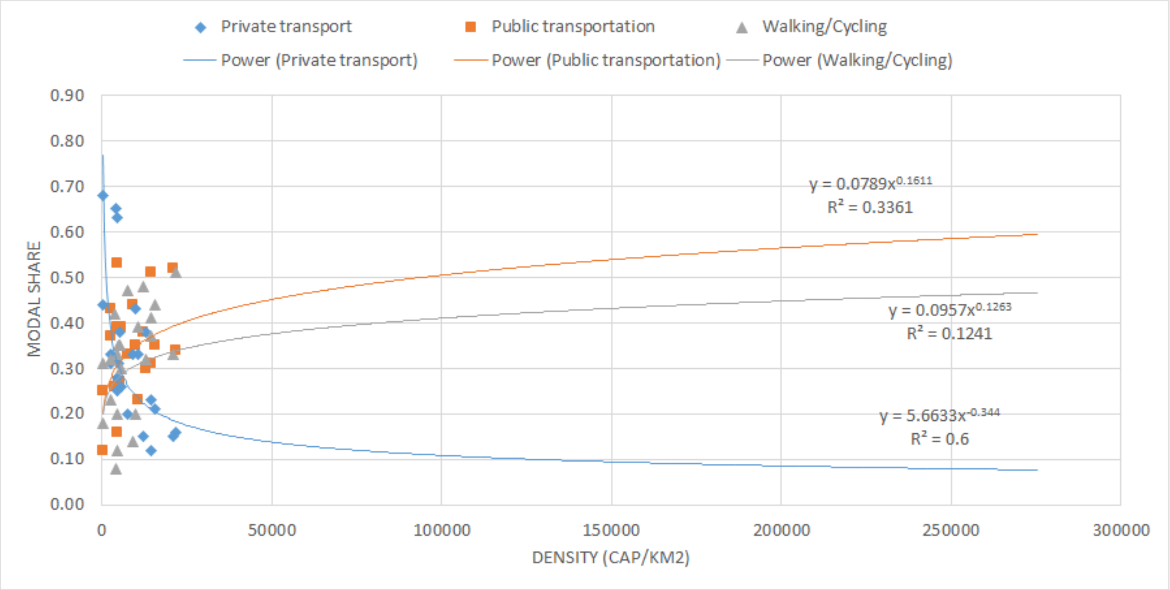

Figure 6: Data for modal share in 23 of the world's large cities, and a power function regression for each mode. A saturation point is assumed. The regressions are later normalized such that the sum of all modes is one.

saturation point for the two remaining modes in the higher end of the observational data. The modal shares are then normalized so that they add up to 100%. The energy intensity as a function of density D, including the normalization, is calculated with equation 20.

$$I_{transportaiton}(D) = \frac{5.66D^{-0.344} \cdot I_{car} + 0.0789D^{0.161} \cdot \frac{1}{2}(I_{bus} + I_{rail}) + 0.0957D^{0.126} \cdot I_{walk/bycycle}}{5.66D^{-0.344} + 0.0789D^{0.161} + 0.0957D^{0.126}} \tag{20}$$

The densities in the modal share data is however based on different definitions of area. Some densities are calculated using the total municipal area, and others on the central parts of the city. The different definitions give rise uncertainties when using this data for the regression, and the resulting dynamic modal share is therefore only an approximation. Due to this uncertainty, the dynamic modal share is only used for testing and comparing how much effect such a dynamic modal share could have on the final holistic model. By using an average modal share as in the static approach, the densities are no longer needed for calculations, and this problem is avoided. To increase validity of the model, the static modal share and its accompanying energy intensity (Eq. (19)) is the one used in the model.

Based on the same data, the possibility of a correlation between the urban population and its density was also investigated, shown in figure 7, but no significant correlation was found.

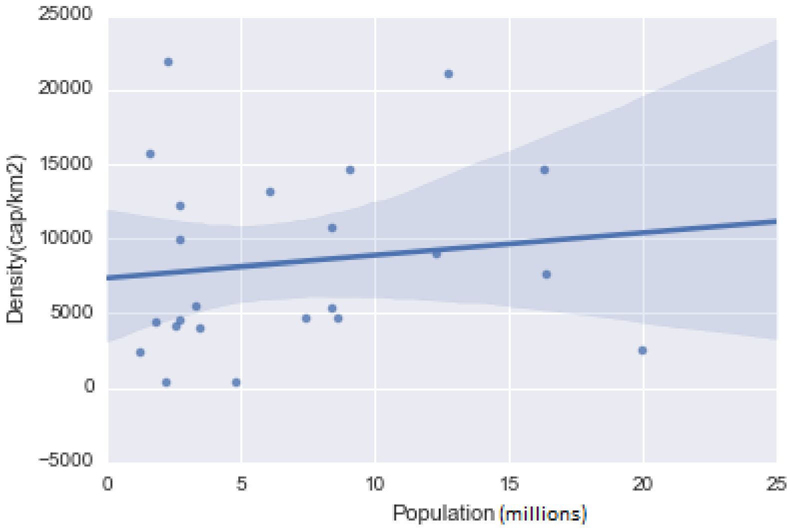

Figure 7: Investigation of a possible correlation between the urban population and its density. Linear regression of 23 data points with a 95% confidence interval shows no significant correlation.

3.4.6 Modeling road infrastructure energy

The road infrastructure energy $E_{roads}(s)$ as a function of stories s is calculated as the product of the energy intensity per meter road, and the total length of the road network, as shown in eq. (21).

$$E_{roads}(s) = I_{road}(2W + 1.5S)\frac{A_{built}(s)}{(W+S)^2} \tag{21}$$

The energy intensity per meter of road I_{road} is from a Life Cycle Analysis (LCA) from literature which is including the extraction of raw materials, production and construction, maintenance, operational energy including road lights and traffic control, and demolition/reuse of materials. A 40-year life cycle is used in this LCA.

The total length of the road network is calculated on the basis that every building has a road surrounding it, as well as a pedestrian zone on each side of that road. As outlined

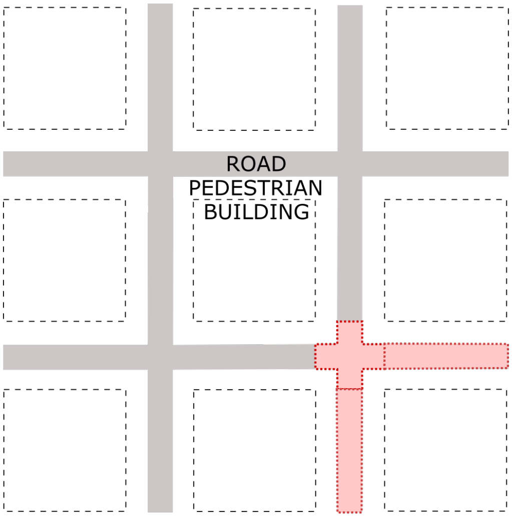

Figure 8: City grid example of the built area. The model output allows for variation of the distance between buildings - the input parameter for spacing is merely the average distance. The stippled colored area is the road length per building, corresponding to 2 times the building width plus 1.5 times the spacing between buildings.

in figure 8, the road length per building is 2 times the building width W plus one road intersection, set to 1.5 times the spacing S. The road length per building is multiplied by the number of buildings to obtain the total length of the road network.

3.4.7 Modeling energy use of elevators

The number of elevators in a building depends on the number of stories s. In addition, it depends on the shape, uses (residential/commercial/combination, etc.), and the number of passengers as well as comfort requirements such as maximum waiting time and transportation time. With a rising number of stories, more elevators are necessary to serve the bigger number of people living in the building. In addition, the elevators will have to move faster to be able to transport more people and to avoid long elevator trips. Buildings above 30-40 stories often have distinct elevators serving the upper and lower half. When the building reaches 60-70 stories it should also be considered to establish lobbies upwards. The inhabitants then take an express elevator to the lobby closest to their floor, and then change elevators. Buildings above 20 stories require many elevators to have a satisfying capacity to transport people.

To estimate the number of elevators needed per building as a function of stories, the newly build high-rise with a state-of-the art elevator system One World Trade Center (OWTC) in New York was used as a case. It has 73 elevators for its 103 stories. The number of elevators was also corrected for building footprint (assuming a building width of 40 meters) and for the big amount of tourists visiting OWTC, as shown in equation 22 [38].

$$\text{Elevators per story} = \frac{73}{103}\left[\frac{\text{elevators OWTC}}{\text{stories OWTC}}\right]\cdot\frac{1600}{4000}\left[\frac{\text{footprint in model}}{\text{footprint of OWTC}}\right]\cdot\frac{10000}{24000}\left[\frac{\text{workers}}{\text{workers+tourists}}\right] \tag{22}$$
$$= 0.118\left[\frac{\text{elevators}}{\text{story}}\right]$$

Data for elevator energy use was requested from the elevator producer KONE. They used their most energy efficient elevator type for calculations, covering stories ranging from 10 to 60 stories. Subsequently, this data was used to calculate energy per building as shown in table 2 (only data per elevator was provided by KONE).

Table 2: Elevator energy use per elevator as provided by the elevator producer KONE, and calculated elevator energy use per building converted with equation 22.

Number of stories	Energy use per elevator (kWh/yr)	Total energy use per building (kWh/yr)	Total energy use per building (W)
10	1830	2159.4	246.34
20	3020	7127.2	813.05
30	7137	25265	2882.2
40	9019	42570	4856.2
50	10660	62894	7174.8
60	12691	89852.3	10250.1

The energy use per building in table 2 was used to make a least squares regression, shown in figure 9, where a quadratic regression was found to be a good fit. The resulting energy use of elevators $E_{elevator}(s)$ as a function of stories s in a building is

$$E_{elevator}(s) = 2.42s^2 + 33.8s - 480 \tag{23}$$

watts on average. To test the significance of elevator energy in the total urban system, the elevator energy in eq. (23) was compared with the other urban elements, and found to only account for approximately 0.4% of the total energy. Due to its small relative impacts on energy use, elevator energy was not included in the final model.

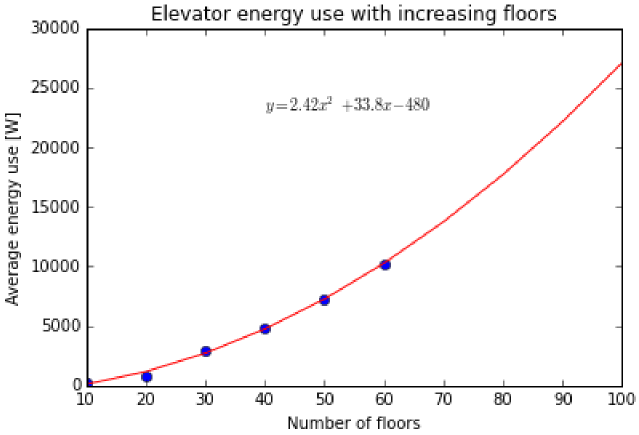

Figure 9: Elevator energy use as a function of stories. Blue dots are data points and the red curve is the regression function based on the data points in table 2.

3.4.8 Modeling energy use in vertical water transportation

The energy use for transporting water upwards in the building to supply the stories above ground level increases with height, due to higher pressure and longer distance. Assuming zero pressure at ground level and one water pump per story, Aronsen et. al. (2015) [39] found the average water transportation energy for a 40×40 m footprint building $E_{water}(s)$ as a function of stories s to be

$$E_{water}(s) = 1.56(s^2 - s) \tag{24}$$

watts on average. This approximation was applied to test how big effect water transportation has on the total system. The water transportation energy use is far lower than elevator energy use, as can be seen in figure 10 where they are shown together. When implementing water energy in the holistic model, it only accounts for approximately 0.1% of the total energy. Its impacts are so small that transportation of water to the stories above ground was not included in the final model.

3.4.9 Connecting entire system and finding optimum

The average total urban energy use per time unit $E_{city}(s)$ for a city with buildings of s stories is found by combining equations (5) (9) (13) (18) (21),

$$E_{city}(s) = N_{buildings}(s)[E_{embodied}(s) + Q(s)] + E_{transportation}(s) + E_{roads}(s). \tag{25}$$

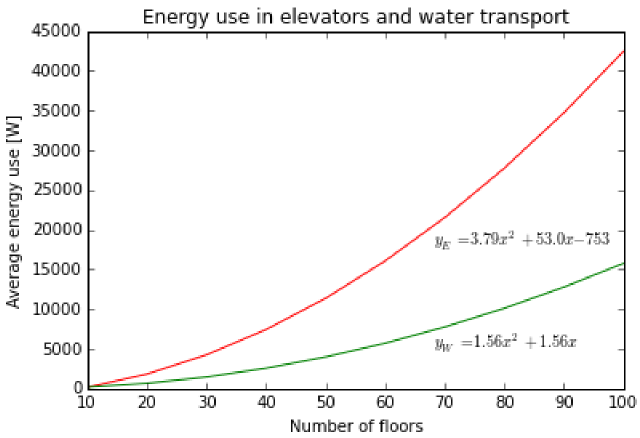

Figure 10: The energy use of elevators (red) and water transport (green) as a function of stories in the building.

This is calculated for all stories ranging from 3 to 60, and a minimum is determined. The minimum energy is then divided by population to get the optimal energy per capita $E_{opt,cap}$. The corresponding number of stories s_{opt}, which minimizes E_{city} (Eq. (25)) is the optimal building height, and from here the optimal urban density D_{opt} can be determined from the population P and the total urban area $A_{total}(s_{opt})$,

$$D_{opt} = \frac{P}{A_{total}(s_{opt})}. \tag{26}$$

These are optimal values for the given set of input parameters. The next step is to see how these change for changing parameter values. How this is done is described in chapter 3.5.

3.5 Analysis of parameters' influence

3.5.1 Analysis of uncertainties and sensitivities

Any model representing reality will have uncertainties in its results. These uncertainties arise from uncertainties in input parameters that propagate and affect the output, and from the simplifications made in the model definition. No model is better that its premises and assumptions, and even when the model is good, no results are better than the input data. In addition, a sensitivity analysis can give valuable insight into the system in question by ranking the influence of the model inputs. Thus, it can quantify which inputs have the largest effect on urban energy reductions, and therefore which measures should be prioritized in policy. It follows from this that an analysis of uncertainties and the sensitivity of the outputs to a change in input parameters are important parts of this work.

The effect that a change in an input parameter has on the output is explored by three different approaches: (i) Variance Based Sensitivity Analysis, (ii) scenario analysis, and (iii) changing one parameter at a time. The parameters investigated are the input parameters in figure 4.

The effect of a change in climate is explored by scenario analysis. Four scenarios for different climates and building technologies are defined. Then the heat loss parameters are changed as described in chapter 3.4.4 so that they correspond to a certain climate and building technology, while keeping all other parameters at baseline values. Having analyzed climate, only one climate is considered for the rest of the research.

A range is defined for the remaining parameters. This range corresponds to what is considered to be upper and lower bounds of realistic values and is used for all the three analysis methods.

3.5.2 Variance based sensitivity analysis

Variance Based Sensitivity Analysis (VBSA) is a global sensitivity analysis, i.e. it measures sensitivity over the whole input space as opposed to locally only. The input space is the chosen parameter range. The VBSA calculates the probabilistic variance of the output variables, which is interpreted as a measure of sensitivity. As opposed to 'one-factor-at-a-time' methods with their well-known shortcomings [40], VBSA also measures the interactions of higher order between parameters which makes it more suitable for a non-linear non-additive model as such [41]. It provides two powerful and versatile measures of sensitivity: (1) the main effects index, which gives the effect of the respective input parameter by itself, and (2) the total effects index, which gives the effect of the input parameter inclusive all of its interactions with other input parameters and therefore more accurately describe the parameter's influence. A significant difference between the two for a given parameter implies the existence of relevant interaction terms for that parameter [42]. The analysis also provides a confidence bound for the indexes. A VBSA is performed on the system outputs using the SAFE Toolbox, which is a peer-reviewed and published code, freely available for academic purposes [43]. This type of sensitivity analysis is computationally demanding, as it requires one model run for every change in an input parameter, to test the effect it has on the chosen output. The sensitivity for both the optimal energy per capita $E_{opt,cap}$, the optimal number of stories s_{opt}, and the optimal density D_{opt} are calculated. For each output parameter, this means hundreds of thousands of model runs. It provides a solid analysis of the relative importance of input parameters.

3.5.3 Scenario analysis

Scenario analysis was performed by defining a set of input parameters that correspond to that scenario. A worst case and best case scenario in terms of energy use gives the upper and lower bound for optimal energy use. A medium case (baseline) scenario can be compared with the worst case and best case scenario to evaluate the uncertainty of the model results. A small difference means the results are valid even when inputs, such as population, are changed. A big difference means results vary with the inputs, and an optimal output of $E_{opt,cap}$, s_{opt} and/or D_{opt} vary with the specific conditions set for the urban area, be it social-, technological-, or design- parameters.

Population P and floor area per capita $FAPC$ are parameters determined by societal factors. How the energy use in the city changes with these two was explored through 12 scenarios, each with a set of values for P and $FAPC$.

3.5.4 Optimal outputs when changing one parameter at a time

To see what effect a change in a single parameter has on the output, all else equal, optimal values were calculated for the whole parameter range, while keeping the remaining parameters at baseline. This was done for the three parameters found to be most influential in the VBSA.

4 Model limitations

The wide scope of the thesis carries with it the implication that the research questions addressed are not exhaustively explored. The model was developed from scratch and is a first attempt at modeling the urban system in such a way. This means that simplifications are made and some urban elements are not included. There is also a limitation set by the lack of data available for parameter estimation and results validation.

4.1 Urban heat island effect

As discussed in the introduction, the urban heat island effect is causing higher temperatures in urban areas than in surrounding areas and thus heat loss is reduced. A warming effect is caused by radiative heat gain from neighboring buildings, wind protection, and so forth. This is, however, a complex process with ongoing research focusing on this specific effect and it is not considered in this model.

4.2 Sunlight exposure

A concern for building dense and tall, especially at northern and southern latitudes, is the effect it has on incoming sunlight. For the same amount of sunlight to reach an area of all tall building as on a lower building one would have to increase the displacement between the buildings accordingly. The amount of incoming sunlight affects the energy use, both because of incoming radiative heat from the sun hitting the building envelope, and due to the need for illumination of the interior area of the building. In warm climates, this can be taken advantage of, as a lower radiative heat load can be a desirable outcome. Narrow streets in a common artifact of historical middle eastern cities, with the advantage of cooler temperatures at street level [44]. This shading also affects the heat load on the building envelope, a fact that is exploited in the experimental eco-city project of Masdar, Abu Dhabi [45]. Including this effect accurately in the model would require a massive model extension, as the benefits and disadvantages of the effect is dependent on a range of factors, including latitude, ambient temperature, window-to-wall ratio, and many more. Simplifications were considered, however, including it would result in increased uncertainties and it was therefore ultimately not implemented.

4.3 Floor Area Ratio and Building Coverage Ratio

A Floor Area Ratio (FAR) is a widely used policy measure in urban planning. It gives an upper limit to the total floor area within a plot of land, while the floor area can be divided into multiple stories. An FAR of 1.0 means one is allowed to build a one-story building over the entire area, a two-story building over half the area and so on.

Building Coverage Ratio (BCR) is an accompanying measure to limit the ratio of building footprint on a plot of land. It is the amount of built area per plot of land, and thus a BCR of 1.0 means the whole area is covered, a BCR of 0.5 means half the area is covered and so on.

Since these measures often set a limit to how dense one can build due to restrictions set by the local and national governments, implementing upper limits on FAR and BCR in the model will allow for more case specific scenarios. In addition, it will make it possible to make the spacing between buildings dependent on building height. This will allow for more realistic modeling of urban density based on today's regulations in a specific urban area. Such case-specific modeling can be considered for further development of the model. In this thesis, however, the goal was to find an optimal urban structure in terms of energy use, and thus, these policy regulations are neglected; the spacing between buildings is not varying with building height.

The regulations for FAR and BCR vary widely around the world and also within countries and cities. Within Tokyo, a highly dense city, they vary from 0.5-13 and 0.3-0.8 respectively [46]. The optimal results of the baseline scenario in this model has an FAR of the built area that ranges from 2.8 to 11. The equivalent FAR of the total urban area ranges from 1.9 to 7.3. The results of this model are thus comparable to the regulations in Tokyo.

4.4 Complicating real life conditions

In a complex system such as a city, there is a range of complicating factors that will affect the outcome of energy calculations. For instance, the soil conditions at the site where the building is erected should ideally also be taken into consideration, as the foundation of the building must be scaled to withhold the weight of the building. In muddy soil, an amount of the soil proportional to the weight of the building need to be removed for the ground to withstand the gravitational forces of the building materials, which results in a greater embodied energy. This is one example of real-life complications to this simplified model. Another effect not taken into account is the increasing amount of area needed for internal structural bearings as a building reaches higher. In super-tall buildings such as Burj Khalifa in Dubai, which is currently the tallest building in the world, usable floor space at the lower stories is reduced significantly due to the structural materials and thus building taller will not result in a proportionate increase in usable area. In fact, as setbacks[1] in building form become increasingly necessary with building height, taken to the extreme in spear-like shaped Burj Khalifa, gross floor area only increase with the square of building height, while it can increase with the cube in buildings such as the Willis Tower in Chicago [47]. For these reasons the assumption used in this model that gross floor area is independent of height is a simplification, however, it would not be very important, if at all, in the ranges of optimal building heights found in this study.

Such complicating real life conditions will always be present as an uncertainty in every model attempting to represent reality. Instead of including each and every one and thus creating an ideal model that will perfectly predict reality (such a model can never be achieved), one should include the most influential and keep in mind that it is not a perfect representation of reality. It can, however, tell something about general trends, and give valuable insight into the system in question. When the effect of an element is not included, the system should as far as possible be modeled in a manner that makes it widely valid and applicable. This model was developed such that it is valid in a wide range of cases. For example, solar irradiation was not included, but buildings can be

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[1] A setback is a step-like recession of the wall which is used to distribute gravity loads by reducing the footprint of upward stories.

dispersed in an arbitrary manner across the area. This leaves room for an urban planner to choose the appropriate orientation and distribution of buildings to achieve the desired amount of sunlight to reach them, while results are still valid for the included elements and assumptions.

5 Results

The results of this thesis are twofold. A holistic model for simulation of density related urban energy use has been developed, which lays the basis for future expansion and development, and, an article is presented, using this model, with its analysis of the energy dynamics of the urban system in relation to density.

The presented model includes many characteristics of the urban energy system and relates them all such that their interactions can be analyzed. Thirteen indicators of energy use in relation to urban density have been explicitly investigated, with the number of stories in a building beeing the main variable determining urban density.

A summary of the results from the paper follows. Figure 11, 12, and 13 show some of the main results. The results presented in the article indicate that high urban density results in lower per capita energy use. This is especially true up until a certain density is achieved, at which point the benefits of increasing density further are no longer significant. A further increase in density will eventually result in higher energy use, which means there exists an interval of optimal densities. The optimal density varies greatly with the indicators.

The heat loss of buildings, and thus the insulation technology, have the biggest potential for energy reductions. After heat loss, the societally determined indicator of floor area per capita is influencing urban energy use the most, and the design- and technologically-determined indicator building lifetime is almost as influential on energy use. Together with the energy intensity of buildings, the lifetime is greatly affecting the embodied energy in buildings. The optimal number of stories, which in turn determine urban density, is fairly independent of floor area per capita but is as can be expected, highly dependent on the lifetime and energy intensity of buildings. In a city with optimal density, per capita energy use is increasing with a rise in population. This is due to the larger area and thus higher

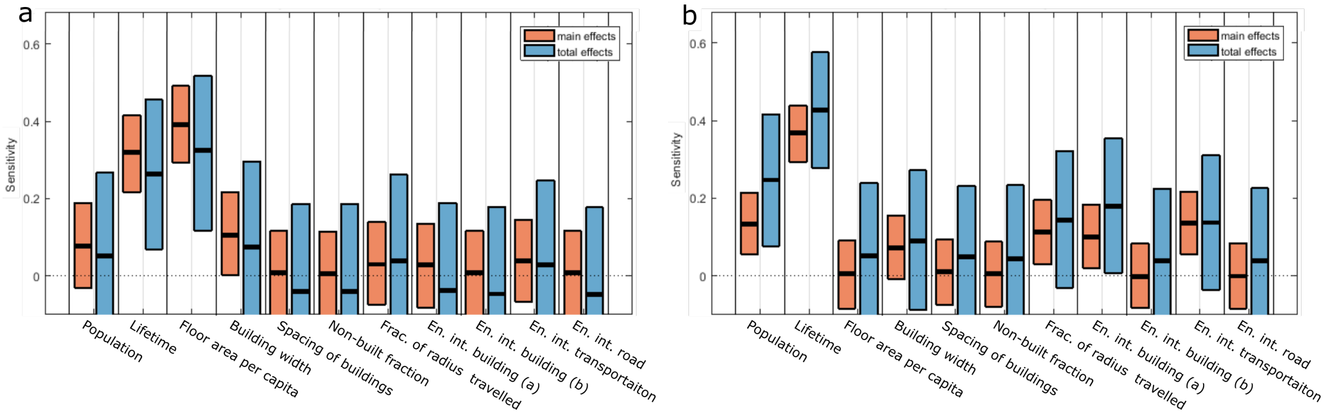

Figure 11: Variance based sensitivity analysis of optimal (a) energy per capita and (b) number of stories; with confidence bounds. The *main effects index* is showing the influence of the parameter alone, relative to the other parameters, while the *total effects index* is including interaction with all other parameters.

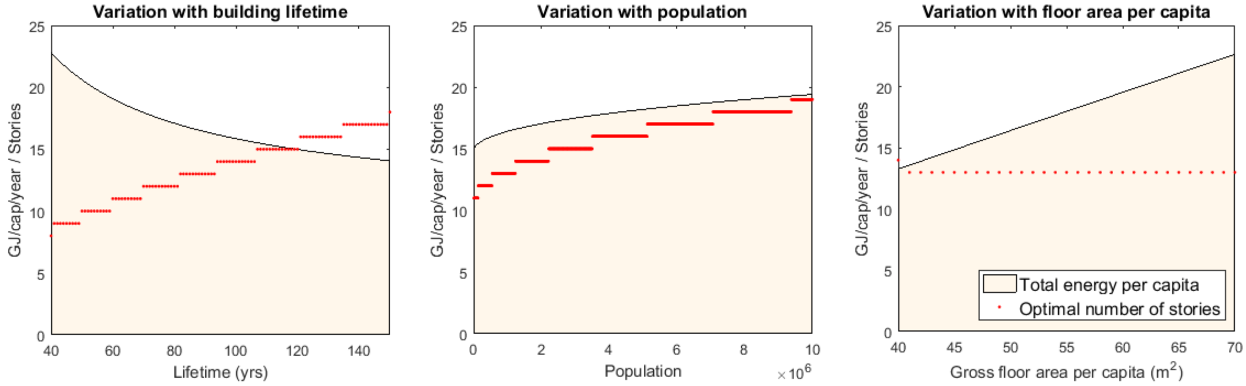

Figure 12: Showing how the optimal energy per capita and optimal number of stories change for variations in the three most sensitive parameters, while the remaining parameters are kept at baseline.

transportation energy as a result of the longer distances traveled. The energy intensity of transportation is increasingly important for large populations and floor area per capita, and with its increasing importance, it is encouraging taller buildings and thus higher density. This means that a higher population encourages building taller. The optimal building height for a given population and building lifetime is in the range of 7-27 stories, as is argued for in the article.

Elevator energy and the energy needed for transportation of water to the stories above ground are not impacting neither urban energy use nor optimal density and building height in any significant way.

Road infrastructure energy is quite insignificant in comparison with the overall energy.

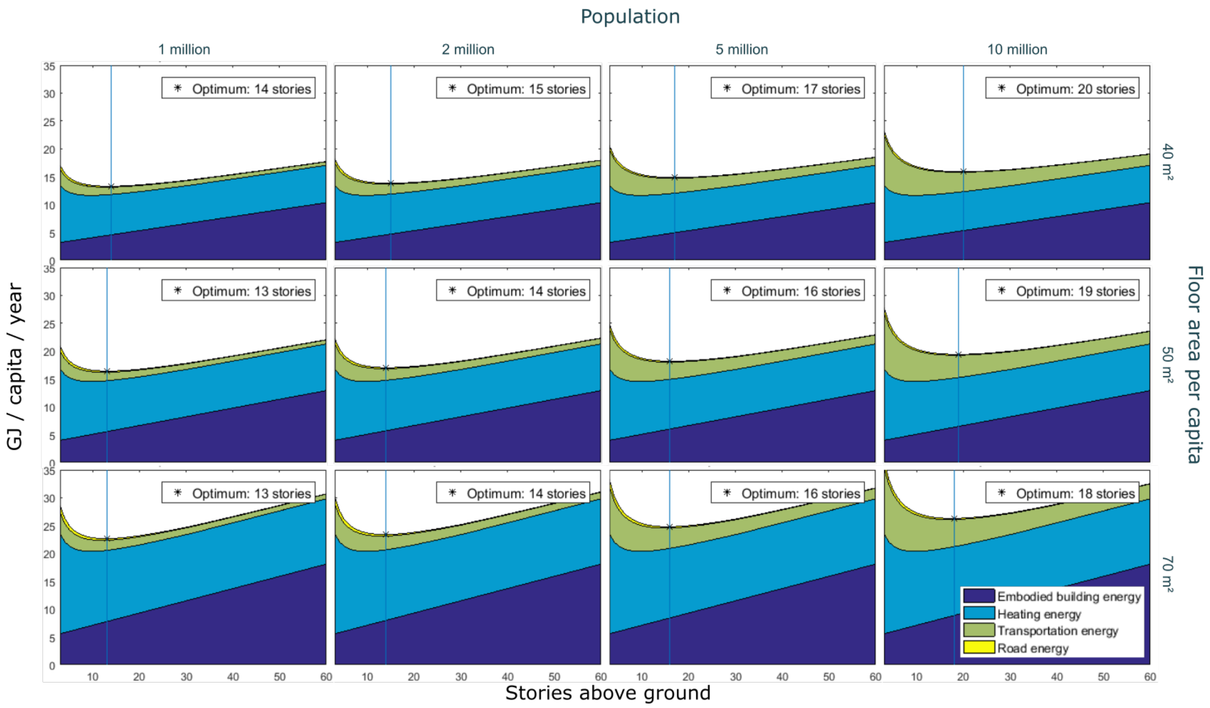

Figure 13: Energy consumption per capita and optimal number of stories for varying floor area and population. Modal share is unchanged.

This study does, however, only concern urban areas that are already compact, and does not apply to areas with big urban sprawl. These results are valid only for compact cities where the benefit of a further increase in density is assessed.

6 Conclusion and policy implications

A proposition for the thesis problem description and research questions was that a holistic approach to a mathematical framework would make possible a deeper analysis and understanding of the urban energy metabolism. The model has proven to be a useful tool for investigation of energy use in the urban system, in relating specifically to density, and also for a wider analysis of urban energy use on a higher level. With it, the relative importance of urban parameters is assessed, and valuable insights into the dynamics of the urban system are gained. The model has shown to be worth developing further.

In conclusion, there are energy benefits of high urban density. The benefits are largest for cities with (i) large populations, (ii) high heating energy need, and with (iii) non-energy-intensive, long-lifetime buildings (low embodied energy), and vice versa. Any measure to reduce transportation energy, such as mixed-use areas, will reduce the benefits of high-density. Building heights significantly higher that the average heights of today's cities should be considered by policymakers and urban planners. Policies should ensure a high minimum lifetime requirement for building design, especially for tall buildings, which have large potentials for energy savings. These are relevant observations with policy implications, however, the model needs further development to reduce uncertainties and to arrive at more exact values for use in city planning.

7 Further research

The current model is a first approach to modeling a complex system with feedback mechanisms and interconnections. Including elements not included here will increase the validity of the model. In particular, the effects of the urban heat island and the exposure to sunlight should be prioritized. Of the two variables described in the literature as having a high incidence on urban energy consumption, but which are not included in this study, both are related to these two effects. These variables, aspect ratio, and urban horizon angle, are high-incidence variables directly relating to density. Increased spacing between buildings as they reach taller is one way of implementing this. Floor Area Ratio and Building Coverage Ratio can be considered for inclusion in a model extension. The effect that green areas have on temperature should also be investigated further. Other factors influencing density related energy use, but which are beyond the scope of this study include space cooling and the scale benefits of infrastructure and services. There are more factors influencing energy use in cities than urban density, for example, mixed use areas is a factor influencing travel need but which is not directly related to density. The effect this has on transportation reductions should be evaluated in relation to this model.

The parameter estimations in this thesis are based on the best available data, which unfortunately are scarce. An effort should be made at improving parameter estimations to reduce uncertainties. Variations in current construction technology and future improvements in construction technology could greatly impact how the embodied energy in buildings vary with height. This will affect energy use and urban density through a higher optimal number of stories. More accurate and case-specific parameter estimations should be applied in future models.

8 Paper: Impact of urban density and building height on energy use in cities

The paper *Impact of urban density and building height on energy use in cities* follows in its original format. Submitted and currently under peer-review for the SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki, and to be published in Elsevier Energy Procedia.

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Impact of urban density and building height on energy use in cities

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Abstract

Compact cities have been attributed to lower per capita energy use. However, the complexity of relationships between the elements that constitute energy consumption in the urban system is poorly understood. Little or no research exist on the relation between energy costs of building taller, and transportation and infrastructure energy benefits of building denser. This study provides a theoretical assessment of how energy use is related to urban density in a densely populated area, to aid the development of sustainable cities and land-use planning. The paper builds a holistic parametric model to estimate the total urban energy use for space heating, embodied building energy, transportation energy, and road infrastructure energy, and how these relate to urban density. It does so by varying building height and other urban characteristics related to density, with the aim of identifying the most influential parameters with regard to energy consumption. The possibility of an optimal building height and urban density is also investigated. A much denser and taller city structure than what is normal in cities today appears to be optimal for low urban energy use. The most influential urban density indicators are found to be the dwelling service level (m^2/cap) and the building design lifetime. Transportation energy becomes increasingly important with a rise in population. Results indicate that depending on population and building lifetime there exists an optimal building height in the range of 7-27 stories. Climate is found to significantly influence the energy results. These preliminary findings are indicative of general trends, but further research and development of the model are needed to reduce uncertainties.

Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.

Keywords: Building height; tall buildings; urban density; land-use planning; theoretical urban modeling; embodied energy; transportation energy; heat loss energy; road infrastructure energy; sustainable cities

1. Introduction

Compact urban form is identified by the IPCC as an important sectoral climate mitigation measure [1], attributed to lower per capita energy use [2–7], mainly due to a reduction in transportation energy. Newman and Kenworthy [2] demonstrate that urban density is an important explicative factor of transportation energy use in big cities. The general trend of denser cities consuming less transportation energy per capita has been confirmed by others [8], and evidence suggests that the modal share of walking/cycling is higher in high-density communities [9]. Open space, i.e. the fraction of the urban area not built up, has also been identified as a significant variable in transportation energy [6]. A compact city structure, however, affects more than distances traveled and mode share. Studies claiming that higher urban density has energy benefits often only focus on one, and neglect other variables [7], while energy use of cities should be compared on a broad basis to be useful in planning [4].

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Cities characterized by high density are housing more people within a certain area. This typically leads to a trend of building taller as to provide enough dwellings to house the population. The height of buildings is affecting mainly two aspects of the buildings' energy use. Firstly, the heat loss of buildings is dependent on its physical dimensions [10,11]. The energy needed for heating, all else equal, can be shown to be lower in tall buildings than in low structures due to a higher floor-area-to-envelope-area ratio. The heat loss to the ground and through the roof is divided by an increasingly larger floor area as the building reach higher, while the wall area per story remains the same. Secondly, the embodied energy of buildings is generally increasing with building height. A few studies have examined this trend [12–14], but to our knowledge, no consistent comparison of how the embodied energy of buildings vary with height exist.

Urban economists provide one other viewpoint on urban density by pointing out significant economic benefits originating from increased scale and density, as the public services and infrastructure are shared more efficiently. [15,16]

A hybrid life-cycle assessment model by Norman et al. [5] compares energy in construction materials for residential dwellings, utility and road infrastructure, operation of buildings, and transportation. They show that building operations have the biggest energy reduction potential and that high urban density is less energy intensive. There is, however, a much greater energy benefit per capita than per m^2. This again suggests that the floor area per capita (FAPC) is an important determining factor. As their study demonstrates, building operational energy is one of the biggest urban energy consumers. In Europe, the residential sector alone accounted for 26.6% of the final energy consumption in 2005 and is one of the sectors with the highest potential for energy efficiency [17]. Of a building's energy demand, about 80-90% is operating- and 10-20% is embodied energy. This ratio is, however, changing as technologies for energy efficiencies are applied to reduce operational energy [18]. Several reports on world energy use show that cities consume up to 75% of global energy and account for 78% of anthropogenic carbon emissions [19,20]. The need for addressing and understanding environmental and energy issues of urban areas is correspondingly widely acknowledged. If cities are part of the problem, they must inevitably also be part of the solution [7]. If current urban expansion trends continue, the urban energy use will more than triple from 240 EJ in 2005 to 730 EJ in 2050, and forecasts show that the global urban footprint will triple from 2000 to 2030. According to research the largest mitigation potentials lie in cities where infrastructure and associated behavior is not yet locked-in [3]. How cities develop their spatial urban form will lock in energy use patterns for decades. The combination of increasing urbanization and not yet locked-in infrastructure opens a rare window of time for realizing energy savings through overall city planning.

How an overall city structure influences energy consumption is, however, still poorly understood. As a key instrument of densification, tall buildings may prove important. Yet, the overall energy-saving potential of building taller and denser remain largely unclear. Other authors have acknowledged the need for research both on energy related to building height and on how the overall energy usage of cities is affected by its structure through a holistic approach [7,21]. Realizing that there will be a need for large-scale urban development in the coming years due to population growth and urbanization, this paper attempts to address this knowledge gap. Most studies on energy related to density are statistical, and which factors actually determine the reduced energy consumption typically remain uncertain. Since statistics concerning detailed energy consumption are usually poor [4,6,22], a theoretical model could provide a more coherent energy analysis. To our knowledge, no attempt has been made at modeling a city's energy use with a holistic parametric modeling approach thus far. The ambition of this paper is to arrive at a more profound understanding of energy use related to density in cities. This paper attempts to answer the following questions:

- Which are the most influential urban density indicators with respect to reducing urban energy use?
- Is there an optimal urban density that will minimize building- and transportation energy use for cities with varying populations?
- Does there exist an optimal number of stories to achieve this density?

This paper is organized as follows: Section 2 describes the mathematical model and estimates the system parameters; Section 3 presents the results, provides a sensitivity analysis, a discussion of the results, and finally, Section 4 summarizes the main findings and proposes suggestions for further research.

Nomenclature

s	above ground story count
EE	initial embodied energy
FAPC	floor area per capita (gross floor area)
GFA	gross floor area
IPCC	Intergovernmental Panel on Climate Change
VBSA	variance based sensitivity analysis

2. Methods

2.1. System definition and model assumptions

In this study, we have used energy consumption as a proxy for global warming potential from cities. This is thus a first attempt to develop a mathematical model to investigate the relationship between the energy use in cities and the numerous parameters that determine urban density. The model is not complete, however, it provides interesting insights on the complex urban metabolism. The research questions were examined under varying a range of spatial, societal, and technological urban characteristics. In this research, urban density is measured mainly through the variation of building height. The influence of other parameters is also investigated, however, the built-area to total-area ratio is constant in each scenario. As such, this research does not attempt to establish the best "building density", but rather models an already compact urban area in which the height of buildings is varied. Classical planning theory would suggest more spacing between buildings of higher altitude for sunlight, sky view factor, wind load considerations etc. [23] but later in the article, it is demonstrated the spacing between buildings would not influence the results to a large degree.

The urban system was analyzed to find which energy consumers might be affected by urban density. Only the most important factors assumed to be correlated with density and building height were included. As such, the model does not calculate total energy consumption, but rather how the elements correlated with density and building height are affected. The elements examined are initial embodied building energy, energy need for heating, transportation energy, and road infrastructure energy. Elevator energy and the energy needed for vertical water transportation inside buildings were included in an early phase but found to be insignificant and were excluded from further investigations. Elements that have been excluded due to the complexity of their effects, although potentially significant, are the urban heat island effect and solar irradiance. The urban area modeled is homogenous in the sense that all buildings are of the same height, have the same square footprint (projection on the ground), the same embodied energy and lifetime. However, the buildings may be dispersed in an arbitrary configuration over the given area. In a similar manner, other model parameters are to be considered average values, i.e., the floor area per capita has fluctuations such that some people occupy more space and others less. The spacing between buildings may be smaller in some cases and larger in others. The same goes for the distance people travel.

The total area is a circular disc since this minimizes all relative distances, in which one-third of the area is a non-built environment, such as public parks, rivers and lakes, mountains, forests etc. The remaining two-thirds is the built environment, whose size is determined by the number of buildings and the spacing in between them (roads and pavement). The number of buildings is again determined by the number of stories in each building. The total built area must satisfy the population's need for usable floor area (apartments and commercial area), which is here considered to be 85 % [24] of the gross floor area (GFA).

The FAPC is considered to be the GFA of both residential and non-residential buildings, where the latter include several categories (office buildings, hospitals, schools and universities, hotels and restaurants, buildings in wholesale and retail trade). To find a suitable value, the median value of the EU15 countries was calculated with data from [25], resulting in 51.5 m^2 of gross FAPC.

When determining the width of buildings and the spacing in between them, a qualitative investigation of the maps of Manhattan, NY, and Paris, France, was undertaken. Based on this, a building width of 35 meters with a spacing of 20 meters was chosen.

The ceiling-to-ceiling height h of each story s is set to 3.4 meters [26] for buildings of 30 stories and less. For buildings reaching higher, i.e. 31 to 60 stories, an empirical formula for the height of residential buildings from a study conducted by [27] is applied, which reduces h slightly for consecutive stories.

The chosen parameter values, as well as their extreme cases that constitute their range, are summarized in Table 1. The medium case corresponds to the baseline values, which in addition to the table values has the climate and building technology representing Belgium and a population of 1 million.

Table 1. Parameter values in the baseline- and two extreme cases, used as ranges for the inputs. Climate and population come in addition.

Scenario	Gross FAPC (m^2/cap)	Lifetime of buildings (yr)	Building width (m)	Spacing between buildings (m)	Fraction of non-built area	Fraction of radius travelled ($person^{-1}$ day^{-1})	En. int. buildings (as function of s) (GJ/m^2)	En. int. transportation (J/person-m)	En. int. road infrastructure (TJ/km)
Worst case	70	40	20	30	1/2	3	*95% confidence, upper bound*	1601	27.2
Medium case	50	90	35	20	1/3	2	$0.24s+5.35$	908	22.4
Best case	40	150	50	15	1/4	1	*95% confidence, lower bound*	511	22.4

2.2. Model description

A parametric mathematical model was developed for calculating and comparing the energy consumption of the included elements for all stories ranging from three to sixty. The conceptual mathematical model for calculating total energy in a city with buildings of *s* stories is outlined in Fig. 1. This procedure was run for all stories and the optimal was determined for each configuration of model input parameters. An individual description of each of the city's energy consuming elements follows next.

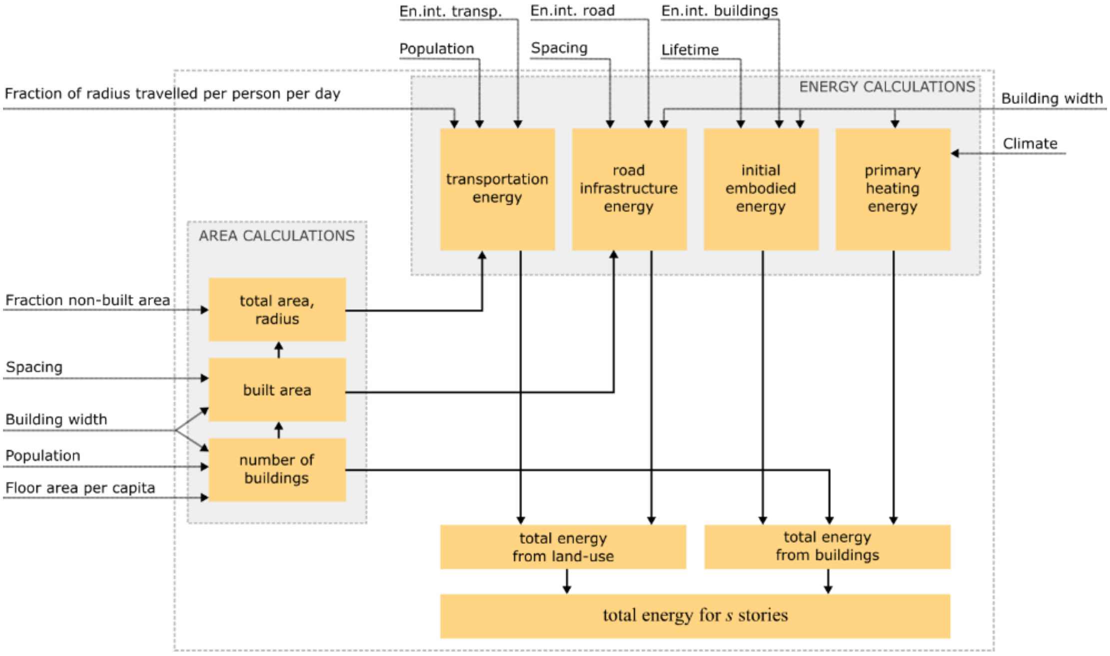

Fig. 1. Conceptual mathematical model for calculation of city energy for *s* stories. This procedure is run for all stories from 3 to 60 and an optimum is determined for all combinations of input parameters.

2.3. Embodied energy

When building taller, a number of extra loads are put on the structure. Firstly, due to the increase in weight, more load is put on the ground, which requires a stronger foundation. Secondly, the lower stories of the building must withstand the extra weight of the extra stories above. Thirdly, when the buildings reach a certain height, strong winds become a real concern and also requires a stronger structure. These factors all require (i) more materials, and/or (ii) more energy intensive materials (e.g. steel). Thus, a building's initial embodied energy (EE) may be assumed to be increasing with increasing number of stories. EE during the use phase of the building through maintenance and retrofitting is assumed not to be correlated with height and therefore not included. Also not included is the end-of-life (demolition and disposal) energy which is substantially lower [21] than the initial energy and would not significantly influence results; in addition, data simply does not exist [13].

The energy impacts of EE in tall buildings might be prevailing, yet, not much research exist on the topic. Data on the EE, i.e. energy in the pre-use stage of buildings is scarce and inconsistent. Very often system boundaries are unclear, or different choices have been made on: included life cycle stages, included building components, type of building, energy definitions (primary/delivered), the definition of floor area, and when annualizing EE different lifetimes are used. Buildings generally also have different footprints, and different methodologies are used. In addition, there is a particular lack of research on the EE of tall buildings. Nevertheless, a regression was made from the best data available on the correlation between the EE and the number of stories. Data from 68 life cycle energy analyses on buildings [12,13,21,28,29] ranging from 3 to 52 stories were acquired and adjusted per GFA. Due to no particular trend in the data, no distinction has been made between residential and commercial buildings. Many studies did only include energy spent on the manufacturing of materials and not the transportation of building materials to the construction site, neither the energy spent on the actual construction. To adjust for this, the methodology of [21] of adding transportation and construction energy as a percentage of material manufacturing energy, respectively 4% and 10%, was applied. These percentages are calculated by [21] from case studies where all three are included. Results of the regression was a moderate linear correlation (R=0.324) between the per-sqm. primary EE and the number of stories in the building as shown in Fig. 2. This was then used to calculate the EE of buildings ranging from 3 to 60 stories, by multiplying by footprint and stories.

The EE is annualized by dividing it over the buildings operational lifetime. This is the biggest uncertainty in the model, as the lifetime can vary a lot from country to country and with different building technologies. Literature suggests a range from 40 years in China [30] to 150 years in Germany [31]. The uncertainties in the EE intensity are a lot less important, as the amount of years chosen as the lifetime in the annualization has a far greater impact. Considering the study only deals with buildings reaching from 3 stories and higher, and that taller buildings generally are designed to last longer [14], 90 years was chosen as the baseline lifetime.

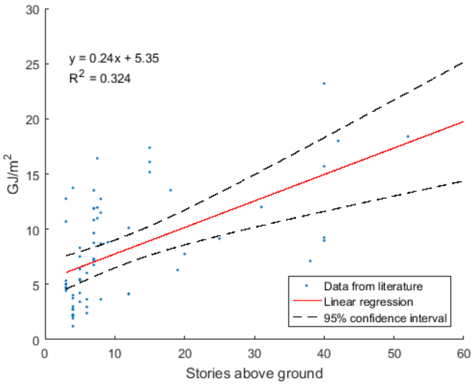

Fig. 2. Initial embodied energy (primary) as a function of above ground story count.

2.4. Heating energy

As the number of stories in a building increase, so does the ratio of floor area to envelope area. Since the building envelope is the main heat sink of a building, the heat loss per floor area will effectively decrease as the building reaches higher. This effect is biggest in the beginning and then levels off with increasing height. The primary energy needed for space heating and ventilation (as a consequence of heat loss) of an arbitrary building was modeled such that the number of stories can be varied. This was done using heat loss parameters from four different countries with differing climates and building typologies. The data for the buildings heat loss parameters were acquired from the EU research project TABULA [32], and the same methodology was generalized and applied for the calculations of delivered energy. A delivered-to-primary energy conversion factor of 1.24, which is the average for the four countries, was added. One representative apartment block building in a non-refurbished state, shown in Table 2, was selected from each country. Subsequently, the model was calibrated and validated separately for each building with data from the same source. Solar heat load as well as issues related to country specific energy carriers and loss in energy transmission is beyond the scope of this study.

Table 2. Description of the four apartment block buildings chosen for the study of heat energy need. [32]

Country – north to south (*climate region*)	Construction finished	Number of complete stories	Heating days	TABULA building variant code
Norway (*national*)	2011	4	249	NO.N.AB.07.Gen.ReEx.001.001
Belgium (*national*)	2012	11	210	BE.N.AB.06.Gen.ReEx.001.001
France (*national*)	2013	6	209	FR.N.AB.10.Gen.ReEx.001.001
Spain (*Mediterranean*)	2007	7	22	ES.ME.AB.06.Gen.ReEx.001.001

2.5. Transportation

With a denser city structure, the inner-city travel distances decrease. Calculating how transportation energy is related to urban density is not a trivial task. In this study, it was assumed that, on a daily average, all residents travel the length equivalent of the city diameter in the baseline scenario (scalable through an input parameter for sensitivity investigations). This includes both personal and commercial transportation but excludes inter-city transportation (which is not directly affected by density). The total area, which is assumed to be circular, was calculated, and the diameter was multiplied by the population to acquire the total distance traveled in one day.

To estimate the energy intensity of the per-person-and-meter transportation, the modal share of 23 of the world's large cities was gathered [33]. There was no significant trend is this data suggesting a relationship between the population of a city and its density. A certain correlation between density and modal share was however present, as previously confirmed by literature [9]. At the densities at which this model operates the modal share was found to be close to a saturation point, and thus an average of the 23 cities was applied as a constant mode share value. The city with the highest share of private transportation, Sydney, and the city with the lowest share, Tokyo (23-Ward), was used for calculations of the range in transportation intensities. The range between the worst case and best base was used for calculating the sensitivity of modal share. The three modes: private transportation (assumed here to be cars only), public transportation (assumed here to be divided equally between bus and rail), and walking and cycling (which has zero energy intensity) and their respective shares are shown in Table 3. Next, the energy intensities of the three energy consuming modes for Japan, which has a high urban density and an efficient public transportation system was acquired from [34], and a weighted average of the per-person-and-meter energy intensity was calculated and multiplied by the total distance traveled. See table 3 for data and calculations.

Table 3. Data and calculation of average, worst case, and best case transportation energy intensities based on different modal shares [33,34].

Transportation mode	Energy intensity Japan [34] (*J/p-m*)	Modal share medium (average)	Modal share maximum (Sydney)	Modal share minimum (Tokyo 23-Ward)	Weighted energy intensity medium (*J/p-m*)	Weighted energy intensity max. (*J/p-m*)	Weighted energy intensity min. (*J/p-m*)
Car	2223	33.4 %	69.4 %	12.0 %	743	1542	267
Bus	774	17.2 %	6.1 %	25.5 %	143	47	197
Rail	185	17.2 %	6.1 %	25.5 %	32	11	47
Walking/Cycling	0	32.2 %	18.4 %	37.0 %	0	0	0
Total	-	*100%*	*100%*	*100%*	*908*	*1601*	*511*

2.6. Road infrastructure

The energy consumption due to infrastructure such as roads, pipes, waste management and so on, is increasing with lower density as pointed out by economists [15,16]. The infrastructure of the city is here represented by the length of road that is required to cover the entire built urban area. Every building has a road surrounding it in the space between it and the neighboring buildings. The roads are assumed to be made of asphalt by low emission vehicles. The complete life cycle, including the extraction of raw materials, the production of construction products, the construction process, the maintenance and operation of the road including road lights and traffic control, and finally the disposal/reuse of the road at the end of the 40 year long life cycle, is included in an energy intensity of 23 TJ/km [35,36], of which approximately half originates from consumption of electrical energy from road lighting and traffic control. The lifetime adjusted energy intensity was multiplied by the cumulative length of the road network to derive the energy consumption of the urban area due to road infrastructure.

2.7. Urban components investigated but not included

The energy consumption of elevators and that of the transportation of water to the stories above ground were also calculated, however, since they only accounted for about 0.4% and 0.1% respectively of the total model energy, they were excluded from the model due to their relative insignificance.

2.8. Variance based sensitivity analysis

Variance based sensitivity analysis (VBSA) measures the probabilistic variance of the output variables, which is interpreted as a measure of sensitivity. It is a global sensitivity analysis, i.e. it measures sensitivity over the whole input space as opposed to locally only. The input space is here chosen to be the range between best case and worst case values in Table 1, and populations from 0.1 to 10 million with climate corresponding to Belgium. As opposed to ’one-factor-at-a-time’ methods with its well-known shortcomings [37], VBSA also measures the interactions of higher order between parameters which makes it more suitable for a non-linear non-additive model as such. It provides two powerful and versatile measures of sensitivity: (1) The main effects index, which gives the effect of the respective input parameter by itself, and (2) the total effects index, which gives the effect of the input parameter inclusive all of its interactions with other input parameters and therefore more accurately describe the parameter’s influence. A significant difference between the two for a given parameter implies the existence of relevant interaction terms for that parameter. [38] The analysis also provides a confidence bound for the indexes. For further reading and a comparison of sensitivity analysis methods, see [39]. A VBSA is performed on the system outputs using the SAFE Toolbox [40].

3. Results and discussion

Energy consumption in cities is a product of many factors interacting. Understanding the influences of each component is key to determining the best land use configuration. Unless specified otherwise, parameters are kept at the medium values in Table 1. Figure 3 illustrate how the urban characteristics area, number of buildings and density vary with population. The spacing between buildings does not vary with building height in the model, which leads to a swift increase in density. Since city area is strictly determined by the number of buildings, a rapid drop in land-use is occurring as the building heights increase; the number of buildings needed is halved for every doubling of building height, so is the area. With a constant spacing and a given building height, density does not change with a changing population. However, the optimal of all these three characteristics vary as the optimal number of stories change.

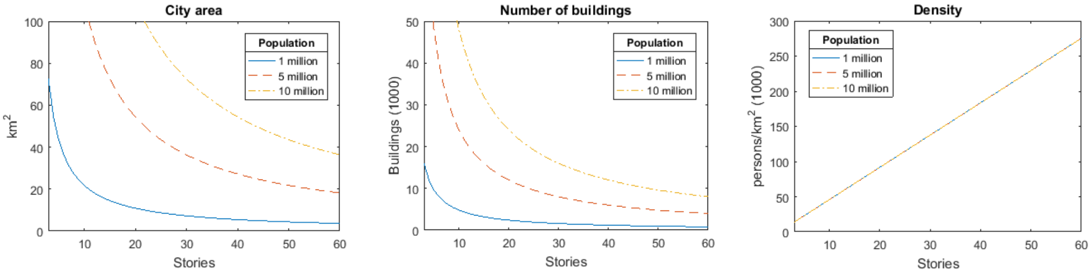

Fig. 3. Urban characteristics of the model with changing populations. Density is unchanged with population, while the optimal number of stories vary.

3.1. Variation with climate and building technology

The variation in energy use per capita with climate shows a clear trend towards higher energy use in colder climates due to larger heat loss, as shown in Fig. 4. The optimal number of stories systematically increases with colder outdoor temperature. The determinant component, the energy need for heating, has an energy reduction potential in cold climates with short buildings. Even though the effect continues it is quickly becoming small when the number of stories is around ten, at which point other urban components become more significant. Colder climates, all else equal, can thus benefit from building tall to reduce heat loss, but only to up to a certain height. With the example population of 1 million in Fig. 4 it rises from 10 stories in Mediterranean Spain to 15 stories in Norway. For a population of 10 million it rises from 16 to 20, while a smaller population of 10 000 suggest an optimal building height ranging from 7 to 13 for these climates and building technologies. However, the energy difference between building at one of the heights within the optimal ranges is not significant, as can be seen for the comparison in Fig. 4. There is hence a small marginal benefit, as long as one is within a certain range. Isolating the effects of heat energy, the benefits are significant only in the beginning.

Road infrastructure, transportation and embodied building energy is not affected by climate given the model’s assumptions. In reality however, a certain added EE may be expected in colder climates due to extra insulation, which to some extent would reduce the energy benefit of building taller. Nonetheless, this is hard to quantify and would require more empirical data. Building technologies such as zero energy buildings and modern insulation materials can significantly reduce the energy need for heating and shift the optimal number of stories lower. Such improvements in technology can have a bigger effect on heating energy savings than the reductions by choosing the right building height demonstrated here, but would at the same time increase EE [18].

This analysis explores only the effect of heat loss and does not include the energy needed for cooling which would have a similar effect to that of heating energy: a decreasing energy need with rising number of stories. It must therefore be taken into consideration that the optima for warmer climates would in fact lie closer to those of the colder climates than what is presented here if cooling was included. For this reason, and for isolation of the remaining influencing factors, only the Belgian climate is considered in the rest of the article and further results should be seen in the light of this climate and the above discussion.

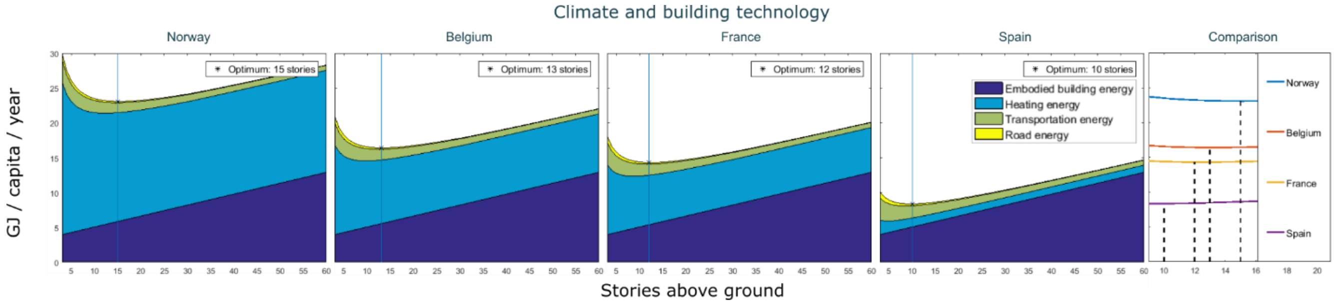

Fig. 4. Variation in energy use and optimal number of stories in four climates. Baseline with population 1 million.

3.2. Relative importance of system parameters on energy use

The relative influence of all input parameters (except climate) on the outputs is provided in Fig. 5. *Optimal energy per capita* is most sensitive to (i) FAPC and (ii) building lifetime, followed by the less influential (iii) building width and (iv) population. The *optimal number of stories* is most sensitive to the (i) building lifetime and (ii) population, followed by the less influential (iii) slope of the EE intensity in buildings, the (iv) fraction of the city radius travelled per person per day, and the (v) energy intensity of transportation. From this we can conclude that 1: They are the model parameters where uncertainties have a big impact and care should be taken to appoint realistic values, and 2: The parameters to which optimal energy is most sensitive are the urban components with largest energy saving potentials. To further explore how the system is affected by the three most influential components (lifetime, population and FAPC) optimal output values were calculated for their whole range, shown in Fig. 6.

The total energy use per capita (Fig. 5a) is not largely affected by spacing between buildings, justifying the model assumption that buildings have the same distance between them irrespective of height. Thus, a city planner can add space to take account for daylighting, sky-view factor etc. without substantially affecting energy use. Neither is the non-built fraction an important factor, contrary to what literature has described as important in some case studies [6]. Road infrastructure is a small part of the total energy budget and it follows that the accompanying energy intensity parameter has low-ranking importance. The two parameters directly determining transportation energy are the fraction of radius traveled and the energy intensity of transportation. They are not of the most important parameters, but together they certainly have an impact. Inner-city transportation has a high interaction with parameters that determine urban area; most notably is that population has a big impact. A higher population increases transportation energy and is therefore encouraging taller buildings which result in higher EE. The footprint of buildings (set by the building width), is as can be expected one of the more impactful urban characteristics. Not only does a larger footprint reduce heat loss, it does at the same time increase density; both of which are lowering the total energy per capita. The most influential parameter on energy use is however culturally determined; the FAPC is the biggest determining factor on energy use, confirming findings from literature. Moving on, changing the constant term in the energy intensity of EE in buildings, b, together with the slope, a, do not substantially affect energy as long as they are within their confidence bounds (Table 1). What *does* consequentially affect EE is the lifetime. The two are inversely related, which means that an increase in lifetime can have a big energy reduction effect initially, and then the effect takes off. An increase in lifetime from 40 to 80 years yield a 43% reduction in EE (Fig. 6). Since the effect is largest in the beginning, policies should ensure a high minimum lifetime requirement for building design; particularly for tall buildings since their EE is higher.

3.3. Optimal number of stories

The optimal number of stories is affected by many interacting parameters (Fig. 5b). In general, the optimal number of stories is more sensitive to inputs than the optimal energy, which confirms that choosing an *exact number* of stories that is optimal would not be meaningful. The marginal changes of building one story taller or shorter around the optima, result in small energy changes. However, there is a *range* of heights that constitute the most energy efficient urban structure. Building at these heights can result in significant energy savings. This range is determined mostly by building lifetime and population. For the combination of a low population of 10 thousand (which result in low transportation energy) and a low building lifetime of 40 years (which result in high annual EE), the optimal number of stories is 7, and in the contrasting case of 10 million and 150 years lifetime the optimal number of stories is 26. When adding the extremes of FAPC in these scenarios, the range only changes slightly, to 7 and 27 stories.

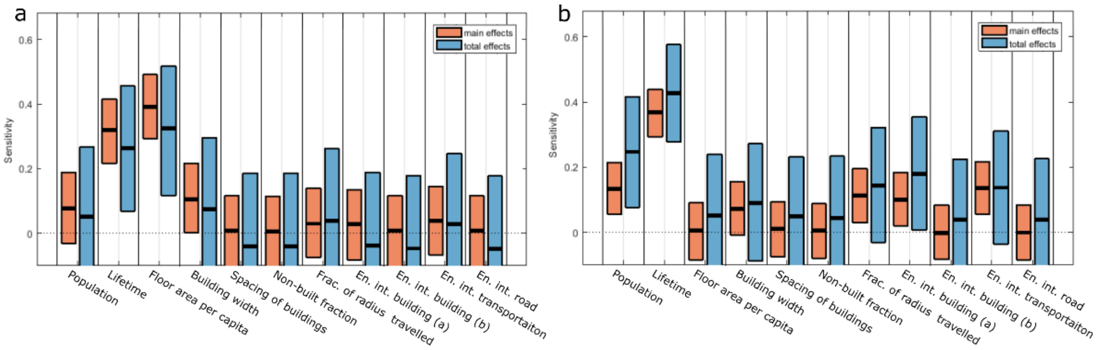

Fig. 5. Variance based sensitivity analysis of optimal (a) energy per capita and (b) number of stories; with confidence bounds.

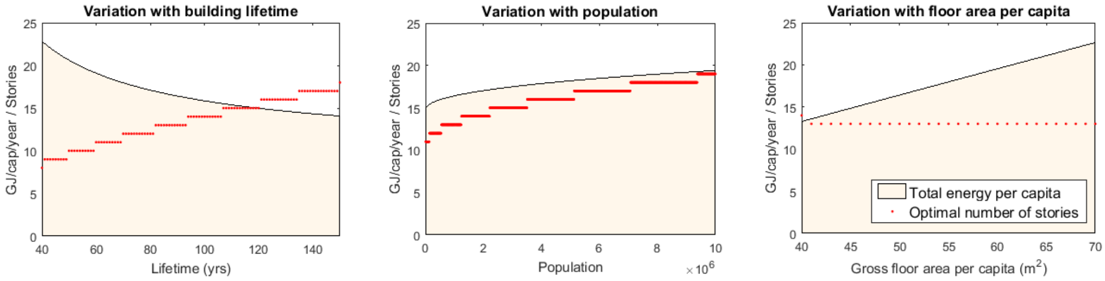

Fig. 6. Showing how the optimal energy per capita and optimal number of stories change for variations in the three most sensitive parameters. (Baseline)

3.4. Optimal urban density

Urban density is closely related to building height, but also to the four spatial land-use parameters. The optimal density in terms of energy minimization however, is dependent on more than spatial measures. A VBSA similar to Fig. 5 was performed on the optimal density, which showed that the EE of buildings (lifetime and energy intensity) is important, as well as FAPC. All parameters have strong interactions and all impact optimal density. The modeled urban densities shown in Fig. 3, are higher than densities reported on real cities. As can be expected, optimal densities, shown in Table 4, are also much higher than most cities of the world. Arguably, this is explained by the combination of the (i) different definitions of density that don't allow for a direct comparison, and (ii) that existing cities are not planned nor built with energy minimization with respect to density as a prioritized goal. Based on the presently available research, policy makers and planners can hardly make such a city a reality as long as research and knowledge on the topic is not available. Other considerations must also be acknowledged in a total city plan, and these results merely indicate what the optimal density would be with respect to energy use.

Table 4 shows the extreme case of energy optimal urban configuration with 9 GJ/cap in the best case, and more than five times higher with 47 GJ/cap in the worst case. Parameter values for the calculations is shown in table 1. The big differences in optimal densities is mainly due to a combination of a higher lifetime resulting in higher EE, and higher transportation energy from the two transportation parameters. The effect of both increased embodied and transportation energy compensate, and make the optimal number of stories remain the same. The total urban area is however scaled up by the combination of the four spatial parameters (including FAPC).

Table 4 shows the optimal results for the worst case, medium case, and best case scenarios, as well as simulations for two real cities. There is little systematic, comparable information on urban densities, as definitions on area included vary widely [41]. The urban density results must here be seen in the light that they only encompass the inner city, with its built area and accompanying non-built area fraction, and should not be compared with population densities including the entire municipal area. For a density comparison based on equal definitions, Manhattan, New York has a built area population density of 35 000 cap/km^2 (2010) [41], which is comparable to the 27 200 cap/km^2 in the worst case scenario in Table 4. The medium case, which is what we consider the realistic scenario, results in an optimal built area population density of close to 90 000 persons per square kilometer for a population of 1 million. The same calculations based on Manhattans exact population and an estimated FAPC[1] of 70 m^2/cap results in 64 000 cap/km^2 as optimal built density, implying an eighty percent increase in built density would be optimal. Some urban areas have far higher densities; Hong Kong is one of the most densely populated areas in the world, but at the same time its FAPC is low. The Kwun Tong district in Hong Kong has a total area density of 57 250 cap/km^2 (2014) [42] on its 126 km^2 area. Running a baseline scenario with the corresponding population of 7 241 700 [42] and an FAPC at our lower bound of 40 m^2 results in an optimal density of 103 000 cap/km^2, again eighty percent higher than its current state. However, the energy savings through such an increase in density, for these already high-density urban areas, are minimal. Even if densities this high are not observed on the city scale, there are smaller areas such as neighborhoods in many cities in the world that exhibit similar and even higher densities.

Table 4. Optimal results for the baseline- and two extreme cases listed in Table 1, as well as for two real cities in the medium case. Population and FAPC are inputs and not results. (Belgian climate.)

	Population (million)	FAPC (m^2/cap)	Stories	Total energy (GJ/cap/yr)	Embodied energy	Heating energy	Transp. energy	Road energy	Area (km^2)	Density, total (cap/km^2)	Density, built (cap/km^2)
Worst case	1	70	14	47	44%	36%	18%	2%	74	13 600	27 200
Medium case	1	50	13	17	34%	56%	9%	1%	17	59 700	89 500
Best case	1	40	14	9	26%	70%	3%	1%	8	132 000	176 000
Manhattan	1.645	70	13	23	33%	55%	10%	1%	39	42 600	64 000
Kwun Tong	7.242	40	18	15	33%	46%	20%	< 1%	70	103 000	155 000

3.5. Energy consequences

Fig. 6 shows how the optimal energy per capita is changing with the three of the most sensitive system parameters. FAPC largely affect the optimal per capita energy use; with a reduction from 70 m^2 to 40 m^2 with the baseline values, there is an energy reduction of more than 40%. Similarly, there is an energy reduction of close to 40% when increasing building lifetime from 40 to 140 years. These are the most impactful parameters, followed by population and building width. However, the cumulative effects of all variables can be much bigger; a more than 80% reduction is achieved from a yearly energy consumption of 47 GJ per capita in the worst case scenario to 9 GJ per capita in the best case scenario (Table 4).

For the optimal density of each population, the per capita energy is increasing (fig. 6). In the case of a small population size of 10 thousand, the energy per capita is 22% lower than for a large population of 10 million. The energy per capita for a population of 5 million is however only 6% lower than for a population of 10 million. The result of an increasing per capita energy with a larger population might be counterintuitive, as a larger population often is associated with higher density. A clear distinction should, however, be made between density (as a measure of persons per area), and the respective population size within that area; density is in theory completely independent of population size. For each of the values in Fig. 6, the city already has an optimal

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[1] The residential floor area is 60 m^2 per capita (2010) [41], and a non-residential area of 16.7% was added.

configuration, and increase with a bigger population occurs due to a transportation energy increase since a larger population requires a larger area. The optimal building height increases to compensate for the larger transportation energy (reducing area), but this compensation is not enough to make up for the transportation. Interestingly, the per capita energy of Kwun Tong is one-third lower than in Manhattan, even though its population is 4.4 times bigger. This clearly demonstrates the importance of FACP in reducing energy use in higher density communities.

To test the effect of including a shift in modal share with higher density, the same calculations were made with a transportation energy intensity decreasing with density based on mode share data from 23 of the worlds big cities [33]. If a shift in modal share is taken into account, the higher energy for an increasing population is reduced to some extent, but the trend is still the same. A reduction from 22% to 15% and from 6% to 4% respectively is observed for the examples above. In this model, road infrastructure is representing infrastructure benefits of higher density. This is only one of multiple infrastructural components of a city that may have scale benefits, and may further reduce the energy increase with population observed here.

3.6. Variations with floor area per capita and population

Fig. 7 provides a visual representation of how the urban energy consuming elements change with the two socially determined parameters: population and FAPC. The optimal number of stories increases with population and decreases with FAPC. Energy per capita is increasing with both in the following way: The FAPC and population are two closely related parameters, as they together determine the total floor area of the city. Both influence the total number of buildings needed, and thus increase transportation energy. However, only FAPC influence EE, heating energy, and road infrastructure, which are all increasing significantly. They are to a large degree affected by FAPC, while unaffected by population. The net effect is that energy use increases more with FAPC than with population. This same conclusion is drawn from the sensitivity analysis and is confirming what literature has to say about energy reductions related to urban density; one of the biggest energy gains from compact cities is due to the reduced dwelling service level (m^2/capita) often associated with compactness. Both of these parameters are however culturally determined and are hard to change by imposing policies. Thus, the latitude in policymaking resides mostly at building the optimal number of stories.

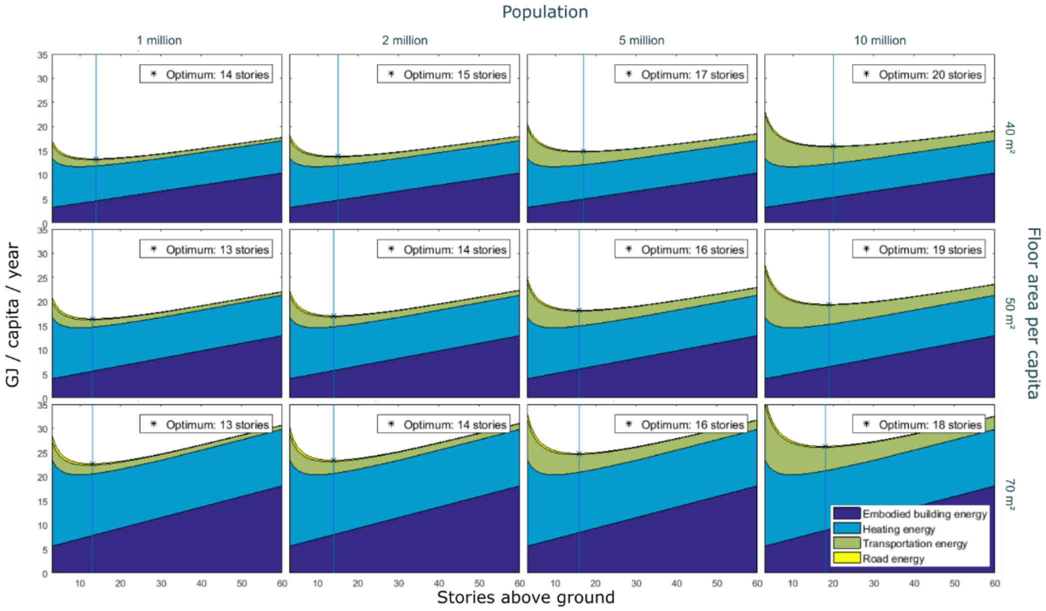

Fig. 7. Energy consumption per capita and optimal number of stories for varying floor area and population. Modal share is unchanged.

3.7. Uncertainties and limitations of the model

There are more factors influencing energy use in cities than urban density. As an example, transportation reductions can also be gained by mixed-use areas, which is another factor influencing travel need but which is not directly related to density.

Other factors influencing density related energy use, but which are beyond the scope of this study include space cooling, increased spacing between buildings as they reach taller, scale benefits of infrastructure, solar irradiation both as a factor of heating and of daylighting, and the urban heat island effect. The energy need for heating in buildings is a complex process, and simplifications have been made in these estimations. In addition, when buildings reach a certain height, building taller will not anymore result in a proportionate increase in usable floor area, as setbacks and higher structural requirements become dominant. The energy intensity of the EE in buildings and how it vary with height is based on the best available data. Variations, as well as future improvements in construction technology, could greatly impact both energy use and urban density through a higher optimal number of stories.

The availability of data for the parameter estimations is sparse, increasing the uncertainties of the results. However, the sensitivity analysis performed to a large degree justifies the results.

On a more general note, the model is a simplified theoretical approach, a first attempt at modeling holistic energy use of cities. Account should be taken that uncertainties are present, and results should be interpreted as observations of general trends rather than exact quantified values.

4. Conclusions

This paper describes a first attempt at modeling how per capita energy use relates to urban density. The main motivation for the present work is that previous work is mostly non-existent and lack the holistic approach. The urban system was modeled by a translation of design characteristics, social-, and technological parameters into indicators that influence the energy use associated with urban density. Among these indicators, the design lifetime of buildings is found to be of great importance due to its big potential to reduce annualized embodied energy. The floor area per capita directly influences the total urban need of built area, and thus strongly impacts per capita energy use. By influencing the energy use of the urban system, these are the most important indicators of an optimal urban density.

The importance of transportation energy in a densely populated area is highly dependent on the population, ranging from 1-20% of the total energy for populations from 10 thousand to 10 million respectively. Thus, results show that the energy benefits of denser cities cannot be attributed to an increasing number of inhabitants, but rather to a decreasing floor area per capita in higher density communities. For a given population and floor area per capita, however, there are substantial benefits of higher density. Both Manhattan in New York, and Kwun Tong in Hong Kong, which are among the densest urban areas in the world, would benefit from an 80% increase in density. This is mainly due to transportation benefits. Reduction in heat loss through building taller and wider also encourage the higher density. However, these urban areas are already high-density, and the energy savings achievable through increasing density further are much smaller than potential savings through applying building technologies which reduce heat loss and embodied building energy.

The individual energy use of the different urban components was found to change profoundly with height. The optimal number of stories increases with lower outdoor temperature and makes it beneficial to build taller, especially in colder climates, while embodied energy increases with height and discourages building too tall.

The main implications of the research are:

- The optimal number of stories are found to be in the range of 7-27, depending on population and building lifetime. The model should be extended with indicators that we intentionally excluded, in order to arrive at more exact values for use in city planning.
- Policies should ensure a high minimum lifetime requirement for building design. This is found to be particularly important for tall buildings.

Results should be interpreted as observations of general trends rather than exact quantified values. The current model needs further development to reduce uncertainties and include other urban energy components related to density.

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