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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.

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Nomenclature

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

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].

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 greater the surface area the more heat is transferred to the environment. Both in hot and cold climates the envelope area to volume ratio should be as low as possible to minimize heat gain and heat loss. If each floor has a fixed footprint and volume, this also holds true for the envelope area to floor area ratio. The energy needed for heating and cooling per floor area, all else equal, can then be shown to be lower in tall buildings than in low structures due to a lower envelope area to floor area ratio. The heat loss to the ground and through the roof is divided by an increasingly larger floor area as the building reaches higher, while the surface wall area per story remains the same. The implication is that stacking more stories on top of each other is beneficial for minimizing heating and cooling energy load [12]. This is however a simplification since it is not taking into account the effect of daylighting and insolation, wind (higher wind speeds at higher altitudes) and humidity. Secondly, the embodied energy of buildings is generally increasing with building height. A few studies have examined this trend [13–15], 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. [16,17]

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 [18]. 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 [19]. Several reports on world energy use show that cities consume up to 75% of global energy and account for 78% of anthropogenic carbon emissions

[20,21]. 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 [7,22]. 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 [4,6,23], 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.

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, here defined as inhabitants per area of land, 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. [24] 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 (EE), 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 EE 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 transportation 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 % [25] of the gross floor area (GFA).

The FAPC is considered to be the usable floor area (UFA) 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 [26], and 50 m^2 was used as a basis for 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 [27] 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 [28] is applied, which reduces h slightly for consecutive stories. The usable floor area of each floor is assumed independent of building height.

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	FAPC (m^2/cap)	Lifetime of buildings (yr)	Building width (m)	Spacing between buildings (m)	Fraction of non-built area	Fraction of radius traveled ($person^{-1} day^{-1}$)	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.

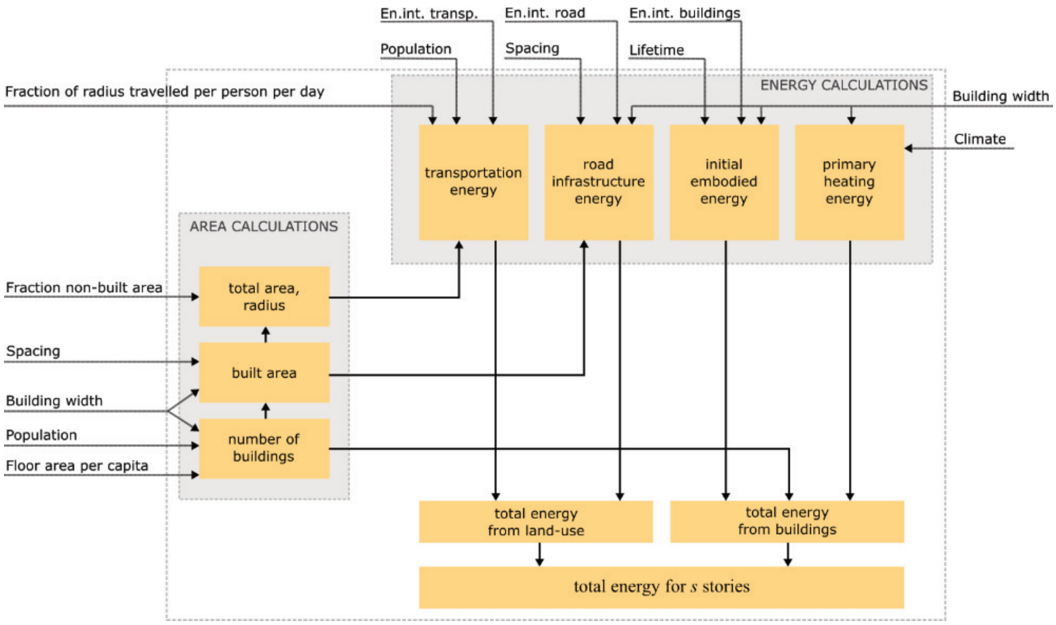

Fig. 1. Conceptual mathematical model for calculation of city energy for *s* stories. This procedure is run for all stories from 3 to 60 and an optimum is determined for all combinations of input parameters.

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 [22] than the initial energy and would not significantly influence results; in addition, data simply does not exist [14].

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 [13,14,22,29,30] ranging from 3 to 52 stories were acquired and adjusted per gross floor area. 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 [22] of adding transportation and construction energy as a percentage of material manufacturing energy, respectively 4% and 10%, was applied. These percentages are calculated by [22] 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 [31] to 150 years in Germany [32]. 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 [15], 90 years was chosen as the baseline lifetime.

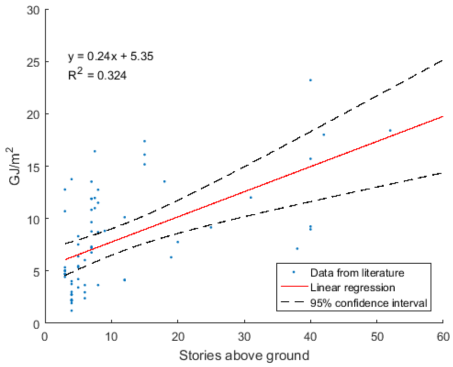

Fig. 2. Initial embodied energy (primary) as a function of above ground story count.

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 [33], 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, are beyond the scope of this study.

Table 2. Description of the four apartment block buildings chosen for the study of heat energy need. [33]

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, is calculated, and the diameter is 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 [34]. 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 analyzing 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 [35], 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 the average, worst case, and best case transportation energy intensities based on different modal shares [34,35].

Transportation mode	Energy intensity Japan [35] (*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 [16,17]. 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 [36,37], 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 [38], 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. [39] The analysis also provides a confidence bound for the indexes. For further reading and a comparison of sensitivity analysis methods, see [40]. A VBSA is performed on the system outputs using the SAFE Toolbox [41].

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.

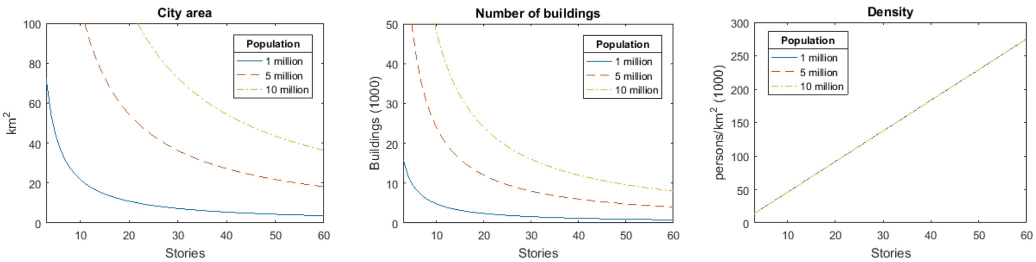

Fig. 3. Urban characteristics of the model with changing populations. Density is unchanged with population, while the optimal number of stories vary.

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 EE 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 [19].

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. Thus the colder climates in this model are more representative also for warmer climates. 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.

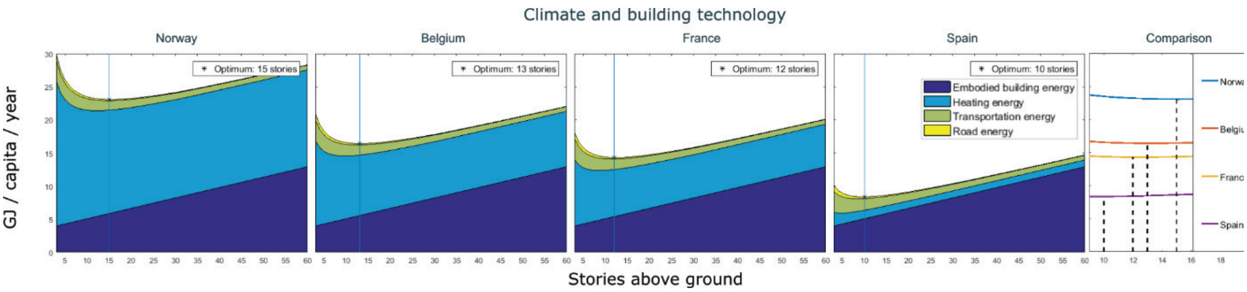

Fig. 4. Variation in energy use and optimal number of stories in four climates. Baseline with population 1 million.

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.

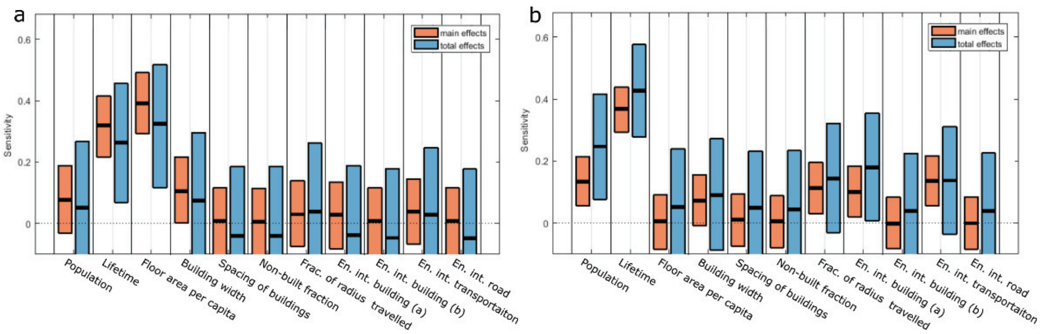

Fig. 5. Variance based sensitivity analysis of optimal (a) energy per capita and (b) number of stories; with confidence bounds.

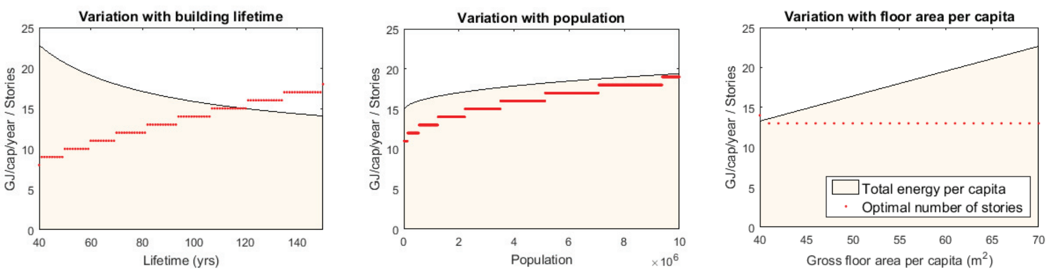

Fig. 6. Showing how the optimal energy per capita and the optimal number of stories change for variations in the three most sensitive parameters. (Baseline)

3.4. Optimal urban density

Urban density (cap/km^2) is determined by building height and the four spatial land-use parameters FAPC, building width, spacing, and non-built area fraction. 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 are not available. In addition, other urban planning 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 are shown in table 1. The big differences in optimal densities occur because the spatial land-use parameters set different requirements for the area needed to house the population. A high EE (mainly due to a short lifetime) discourages building tall. Low buildings result in bigger area requirements and lead to higher transportation energy. The effect of both increased EE and transportation energy compensate and make the optimal number of stories remain the same in the two extreme cases. The total urban area is however scaled by the combination of the four spatial parameters (including FAPC), thus the variation in optimal density.

Table 4 shows the optimal results for the worst case, medium case, and best case scenarios, as well as simulations for two real cities. These simulations of the urban areas Manhattan, New York and Kwun Tong, Hong Kong serve as illustrations of how real urban cases might look like rather than being definite comparisons since climate among other conditions deviates to some degree from the modeled urban area. There is little systematic, comparable information on urban densities, as definitions on area included vary widely [42]. 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) [42], 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 FAsPC[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) [43] on its 126 km^2 area. Running a baseline scenario with the corresponding population of 7 241 700 [43] 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, as already discussed the energy savings through such an increase in density, for these already high-density urban areas, are minimal, and are not significant to the level of accuracy at which these simulations are performed. These densities may seem extreme, but 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.

[1] The gross residential floor area is 60 m^2 per capita (2010) [42], and a non-residential floor area of 37.3% was added after conversion to usable floor area.

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 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 world's big cities [34]. 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.

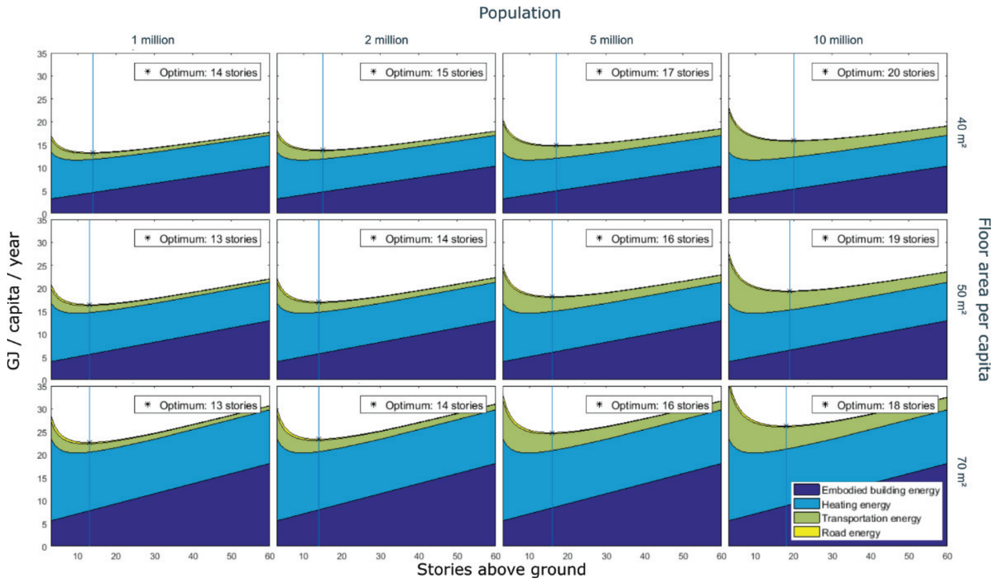

Fig. 7. Energy consumption per capita and optimal number of stories for varying floor area and population. Modal share is unchanged.

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. Heat losses and gains can also be reduced effectively with better insulation.

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. A higher proportion of floor space is needed for bearing structure, vertical transportation and building services. In this study it was assumed that the usable floor space remains unchanged. The energy intensity of the EE in buildings and how it varies with height is based on the best available data. Variations, as well as future improvements in construction technology, could greatly impact energy use as well as optimal 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.

The study investigates the optimal urban structure in terms of energy use of the included elements. The methodology can serve as a tool in a holistic planning process. Visual comfort among other things should also be taken into account in a final urban plan.

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 a further increase in density. This is mainly due to transportation benefits. Reduction in heat exchange with the environment 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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