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Demand-side characterization of the Smart City for energy modelling

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Abstract

This paper presents a new methodology for characterising the energy performance of buildings suitable for city-scale, top-down energy modelling. Building properties that have the greatest impact on simulated energy performance were identified via a review of sensitivity analysis studies. The methodology greatly simplifies the description of a building to decrease labour and simulation processing overheads. The methodology will be used in the EU FP7 INDICATE project which aims to create a master-planning tool that uses dynamic simulation to facilitate the design of sustainable, energy efficient smart cities.

Keywords: Smart cities; energy modelling; building simulation; building characterisation; master-planning.

1. Introduction

More than 50% of the world population currently live in the urban environment – a figure that has been predicted to grow to 70% by the year 2050 [1]. With this migration to urban areas comes an increased demand for energy. By 2030, it is estimated that 75% of global energy consumption will be attributable to cities [2]. In order for urban development to be sustainable new approaches are needed for urban design, city planning, and the production and management of energy. So-called 'Smart Cities' represent an opportunity to improve the efficiency and sustainability of urban areas using an underlying data-driven framework. However, the recent proliferation of data and its availability has not yet led to an increase in sustainable growth and improved urban planning [3].

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INDICATE [4] (Indicator-based Interactive Decision Support and Information Exchange Platform for Smart Cities) is an EU-funded FP7 research project which aims to create a master-planning tool that will support decision makers and stakeholders to transition their cities towards the smart city. INDICATE focuses on and then optimises the interactions between buildings, energy networks and renewable technologies using dynamic simulation models and algorithms. The tool will provide recommendations on optimum renewable technologies, infrastructure improvements and energy management, based on the *planning, carbon reduction, systems integration* and *optimisation* cycle (Fig 1). A function of the tool will be to allow the energy performance of different cities to be directly comparable through the development of a Common City Index.
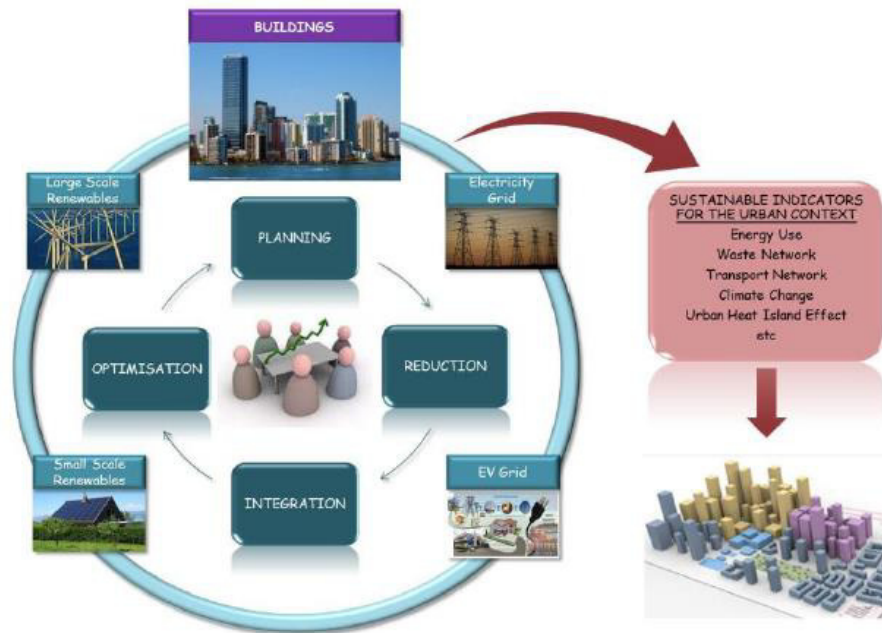

Fig 1. The INDICATE urban planning and resource optimisation cycle

Buildings are central to the concept of the smart city, as they account for over 40% of final energy consumption in the EU [5]. The accurate energy characterisation of buildings is therefore crucial to INDICATE and other urban/master-planning tools (such as CitySim [6] and UrbanSim [7]), as it will govern their ability to produce meaningful results.

This paper outlines a new methodology for building energy characterisation suitable for use in master-planning tools. The methodology takes existing bottom-up building simulation approaches and adapts them for a top-down approach more suitable for city-scale modelling.

2. Modelling approach

In order to model the smart city, it is necessary to identify the relevant components and parameters of the city that will enable its accurate energy characterisation. To this extent, one interpretation of the form of a city is to consider it as a system of subsystems (Fig 2). Many component systems such as the energy supply networks and transport networks combine to form a much larger city-scale system. In terms of the energy performance of a smart city, the component systems of interest are the supply and demand components, the energy networks, energy storage sites, electrical transport networks, and the socioeconomics that govern energy-related behaviour (Table 1).
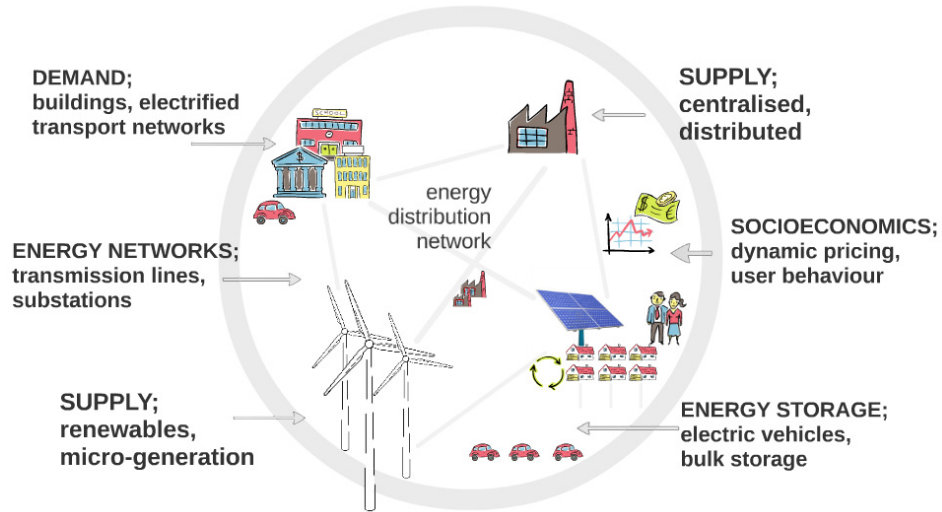
Fig 2: For modelling purposes a city can be considered a system of component subsystems

Table 1. City subsystems and components relevant to energy performance

City subsystem	Component
Supply side	Centralised power stations (e.g., oil, gas, coal, nuclear)
	Distributed power (e.g., combined heat and power, district heat)
	Renewable power generation (e.g., wind farms, hydro, tidal, solar)
Demand side	Buildings (residential, commercial, industrial)
	Transport networks (electric rail, electric vehicles)
	Public services (street lights, telecoms)
Energy networks	Electricity (transmission network)
	Gas (transmission network)
Energy Storage	Bulk storage (e.g., pumped storage hydroelectricity, compressed air)
	PV batteries
	Electric vehicles
Socioeconomics	Dynamic pricing (e.g., Time of Use tariffs, electricity peak demand)
	User behaviour (building occupants, energy consumers)

3. Model structure

From an energy-modelling perspective, it is convenient to characterise the smart city as a collection of nodes and links. The nodes represent the sites where energy is made available to the city system (energy sources), or where energy is used by the city system (energy sinks). The links are the conduits which allow energy to flow between the sources and the sinks throughout the city.

- **Supply Side** energy sources generate energy for use by the city. This generation can occur at conventional centralised sites (e.g., fossil fuel or nuclear power stations); distributed micro-generation sites (e.g.,

combined heat and power (CHP) plants); or more contemporary renewable sites (e.g., wind farms, solar farms, hydroelectric dams).

- **Demand Side** energy sinks are the components of the city which use the energy provided by the supply side. The sinks can be buildings, electrified transport systems, and public services such as street lighting and telecoms.
- **Energy Networks** are the connecting links between the sources and the sinks, such as the energy distribution networks or grids. Transmission lines are used to physically link power stations with buildings. Traditionally, the flow of energy has been in one direction, from the source to the sink via the grid. Of increasing interest within the smart city is the advent of micro-generation sites which allow buildings to act as sources, and the energy they produce to be used locally and/or feed back into the grid and be used by other sinks.
- **Energy Storage** refers to facilities where energy can be retained for use at a later date. In terms of the smart city, this can include batteries of electric vehicles and photovoltaic (PV) systems for discrete, local storage, and also large-scale grid energy storage sites such as pumped storage hydroelectricity, compressed air and flywheels.
- **Socioeconomics** and behavioural characteristics account for the ability of city inhabitants to influence the demand for and consumption of energy. Understanding the behaviour of energy users such as building occupants is important if energy use is to be modelled correctly. Certain policies such as Time of Use (TOU) energy tariffs are designed to impact occupant behaviour to address the balance between energy supply and demand. Such factors should be accounted for in a model of the smart city.

Future work will characterise all of the above model components for the INDICATE project. This paper details the demand-side characterisation, more specifically, buildings.

4. Building characterisation

Fundamental to any real building's energy performance are four property subsets – construction, function, geometry, and systems (Fig 3):

- **Construction** refers to the materials that make up the fabric of the building, as well as the properties and quality of the envelope and the façade. A masonry heavyweight building will have a different energy use compared with a similar lightweight building made from wood (mainly due to thermal mass effects). A building façade consisting of a high proportion of glass will be much more susceptible to solar gains and conduction losses compared with a building that has an opaque façade. Likewise, a building with a leaky envelope will perform differently from a building with a more airtight envelope.
- **Function** refers to the designated purpose of the building, or how the building is used. Whether the building is a public swimming pool or retail outlet will drastically affect the amount of energy it consumes independently of its geometry and construction.
- **Geometry** is the physical description of the building and the space it occupies. The energy consumption of a building will be affected by its size; design; orientation; and location relative to other buildings, geographical topology and features.
- **Systems** provide services to the building occupants. Examples include the heating, ventilation and air-conditioning (HVAC) equipment inside a building that maintain an indoor environment suitable for the intended function of the building. Other systems include the lighting and hot water systems.
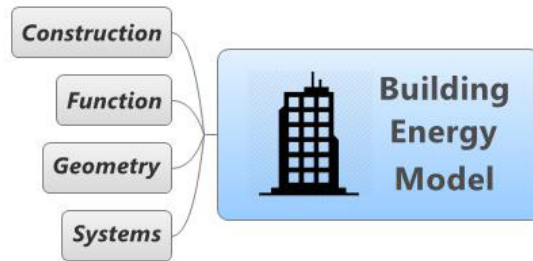
Fig 3. Property subsets of a building that can influence its energy performance

Climate is also a determining factor for a building's energy performance, but not an intrinsic property of the building itself, and so it is not included as a property subset. Climate will however, be included in the INDICATE dynamic simulation model engine.

Conventional building simulation tools such as Virtual Environment (IES) and Energy+ (US DOE) use a 'bottom-up' approach to create a virtual representation of a single building. Accurate 3D geometry of the building's overall form, rooms and zones is created within the energy simulation packages or by using computer aided design (CAD) packages. The geometry is then translated into the simulation environment where the walls, ceilings, roofs and floor are assigned construction properties such as the type of building fabric material. Typically the HVAC systems inside the building and the envelope tightness are then specified before a simulation is performed. This approach can require hundreds of individual inputs to create an accurate model of a single building.

Clearly the scale change involved with modelling cities or large collections of buildings or campuses entails that preserving a similar level of complexity may lead to unnecessarily high labour and computing overheads. It is therefore important to model the building characteristics that will allow the right balance between simulation runtime and simulation accuracy. A 'top-down' approach is more suitable, where groups of buildings are assigned typical properties based on typological classifications such as construction date, region, retrofit history and so on. This removes the need to specify every detail of every building explicitly. A certain degree of accuracy of the simulation results will be sacrificed, but labour and processing times should be drastically reduced.

The top-down building energy model will be integrated into the INDICATE tool and used to calculate the energy demand (gas and electricity) of groups of buildings within the simulation environment. This relies on the assumption that buildings of similar type are geographically grouped together e.g., a residential street will often consist of houses built at the same time. However, building resolution will ultimately be determined by the user.

5. Sensitivity analysis and building characteristics

In order for a building energy model to produce useful results, certain physical characteristics of the building need to be represented in the model. However, some of these characteristics will have a stronger influence than others on the modelled energy performance of the building [8]. Therefore, it is necessary to identify which characteristics yield the greatest energy impact via sensitivity analysis, and then ensure that those characteristics are suitably represented in the model [9–13].

Lam and Hui [14] performed a sensitivity analysis on inputs for a modelled office building in Hong Kong. They found that the annual building energy consumption was most sensitive to internal loads, then window systems, indoor temperature set points and HVAC system efficiencies.

Macdonald [15] states that the three minimum property groups necessary to perform a thermal building simulation are: the thermo-physical properties of the building materials (specific heat capacity, thermal conductance etc.), causal gains (internal loads from equipment and occupants), and air infiltration rate. Macdonald goes on to perform an extensive sensitivity analysis on the different variables of a building simulation. He concludes that the variables which have the greatest impact on the final energy solution are the internal loads within the building, the air infiltration rate, the conductivity of the building insulation, and the weather file used to specify the outdoor environment.

Heller et al. [16] performed another sensitivity analysis on building simulation variables for commercial buildings. In agreement with Macdonald, they found that factors which had the largest effect on simulated energy

performance were the internal loads (mainly due to lighting), the building envelope (glazing, air infiltration, and thermal conductance), and the HVAC system (type, size, efficiency, control). Heller et al. outlined building component packages of best and worst practice for the aforementioned factors, and found that the final energy use of a building could vary by up to 260%, climate-dependent. Heller et al. also considered the energy impact of operator and occupant behaviour. They found that the combined effect of the two could alter building energy use by up to 170%, again, climate-dependent.

Struck [17] and Struck et al. [18] conducted a sensitivity analysis for ten architectural building parameters for commercial buildings (mechanical parameters such as HVAC systems were not considered). They then ranked the parameters in order of impact. The top 5 parameters were glazing G-value (or Solar Heat Gain Coefficient), office-to-gross floor area ratio, glazing U-value (insulation), air infiltration, and façade U-value. In a later study, Struck [19] concluded that the top five parameters that affect building energy use are internal loads, glazing G-value, glass-to-wall ratio, wall U-value and the ventilation air volume.

A more general study on the energy performance of European buildings by the BPIE [5] states that factors that influence residential energy use are the characteristics of the heating system, building envelope, climate, occupant or user behaviour, and social conditions (e.g. not using heating or cooling systems due to fuel poverty, or austerity measures).

Simulations carried out as part of the EU-funded IMPRO-Buildings study [20] showed that across Europe, residential energy use is dominated by heat loss through the building envelope and heat loss due to ventilation and infiltration. Solar gains also play a role in buildings with a high window-to-wall ratio such as high-rise apartment blocks.

From analysis of the above literature, we can conclude that in order to capture or simulate the energy performance of a building the following characteristics need to be considered:

- Internal loads
- Insulation
- Glazing
- Air leakage

- HVAC systems (heating, cooling and ventilation)
- Occupant behaviour
- [Building size]
- [Sustainable systems].

When all other considerations are kept constant (i.e., thermal comfort criteria and heating/cooling loads met), the impact that the above characteristics have on the building energy performance will scale with the size of the building. For that reason, building size has been added to the list of characteristics. Also added to the list is 'sustainable systems', which represents passive and sustainable energy systems, such as solar thermal water heating and photovoltaic systems. Sustainable systems are important to consider in the framework of smart cities and low-carbon building technology, and so are relevant to this work.

A brief description of the building characteristics identified as being important for building energy modelling follows.

- **Internal loads** of a building are the combined effect of the sensible (thermal) and latent (moisture) gains from indoor sources. Occupants, lighting and appliances contribute to the internal loads of a building. At this point it is also important to note one of the differences between residential and non-residential buildings. Heat gains in non-residential buildings are dominated, typically, by internal loads, whereas heat gains in residential buildings are dominated by external climatic conditions such as solar gains and ambient temperature [21]. Therefore, internal loads are more significant when modelling non-residential buildings. In the context of this report, lighting is considered an internal load.
- **Insulation** affects the heat loss rate of the building envelope due to its construction material. In Europe the effectiveness of an insulating material is described by its 'U-value', measured in W/m^2K. Walls, roofs, windows, and floors all have an associated U-value depending on their fabric material. National building regulations commonly specify minimum U-values for new construction e.g., Part L in the UK and Ireland [22].
- **Glazing** or windows have three properties of interest for energy modelling: the level of thermal insulation offered by the glazing, denoted by its U-value, the ability of the window to diminish solar

gains, denoted by its 'G-value' (G-value is expressed as a fraction of solar energy transmitted by the glass), and the combined area of the windows. This is usually expressed as a fraction of the wall area, or the window-to-wall ratio. Building regulations commonly specify maximum values of solar cooling loads that are directly related to glazing proportion [22].

- **Air leakage** of the building envelope. The air change rate of the building is a combination of the infiltration rate (air exchanged inadvertently with the outside due to indoor/outdoor pressure differences and the envelope leakage of the building) and the ventilation rate (intended air exchanged with the outside due to ventilation systems).
- **HVAC Systems** (Heating, Ventilation and Air-Conditioning) are used to provide a thermally comfortable and healthy indoor environment with good indoor air quality (IAQ) for building occupants.
- **Occupant behaviour** related to the energy performance of buildings has been shown to affect building energy consumption by up to 300% [23]. While simulating occupant or user behaviour is still in its infancy, it is important that any simulation tool should at least acknowledge, if not attempt to account for, the impact of the occupant on energy use (see IEA-EBC Annex 66). In its simplest form, examples of occupant behaviour with a building energy impact are switching lights on and off, interacting with the heating thermostat, or the opening and closing of windows.
- **Building size** determines the volume of conditioned air inside the building. The volume of a building, or more specifically, the conditioned volume, is the most important size characteristic for energy modelling, as it dictates the amount of air inside the building that needs to be heated, cooled, or replaced via ventilation. However, volume is rarely reported in building databases, with floor area being a more common metric [5]. It may be necessary to calculate or estimate building volume from information on floor area, ceiling height and number of storeys.
- **Sustainable systems** generate electricity or provide heating or cooling (of air and/or water) for the building at zero or low cost of energy compared to their non-sustainable counterparts. Sustainable systems are integral to decreasing the energy consumption of buildings.

Reverting back to our model of a building for energy modelling purposes (Fig 3), we can classify the above building characteristics into their relevant building property subsets of: construction, function, geometry and systems (Table 2).

Table 2. Building characteristics important for energy modelling classified into their building property subsets

Construction	Function	Geometry	Systems
Glazing	Internal loads	Building size	HVAC systems
Insulation	Occupant behaviour		Sustainable systems
Air leakage			

There will be some interdependency between the identified building characteristics and their impact on building energy use, particularly when accounting for occupant behaviour. This effect was touched upon by Struck et al. [17], although only for different building materials and not systems or properties. Due to the non-linear interactions between building characteristics, weather, building loads etc. the quantification of any interdependencies that may exist between characteristics is complex. Closer examination of interdependency impacts should be the subject of further research.

6. Top-down building characterisation

Studies on building typology such as BPIE [5], TABULA [24], ENTRANZE [25], RECS [26], and CBECS [27] have identified several categories which are useful for describing buildings with similar characteristics. Of particular interest when characterising buildings for energy modelling is:

- Construction date
- Physical form
- Region
- Retrofit history
- Use.

As determined above, the following building characteristics need to be represented in our top-down city model: internal loads, glazing, building insulation, ventilation rate, HVAC systems, occupant behaviour, building size and sustainable systems. With the exception of occupant behaviour, these can all be considered intrinsic properties of a building, and so are more suitable to a bottom-up approach to energy modelling. For our top-down modelling approach we need to generalise these characteristics into the categories defined by studies on building typology: construction date, form, region, retrofit history and use.

It can be argued that the construction properties of a building are dependent on the date of construction, the region where the building was constructed, and whether or not the building has been subjected to an energy performance retrofit. Likewise, the function of a building is dependent on its intended use; the geometry of a building is dependent on its physical form; while the systems inside a building are dependent on its construction date, region, retrofit history and use. Expressed in equation form we obtain:

$$\text{construction} = f \text{ (construction date, region, retrofit history)} \tag{1}$$
$$\text{function} = f \text{ (use)} \tag{2}$$
$$\text{geometry} = f \text{ (physical form)} \tag{3}$$
$$\text{systems} = f \text{ (construction date, region, retrofit history, use)} \tag{4}$$

Knowledge of a building's construction typological categories will enable some of its energy properties to be established. For example, if we know the construction date, region and retrofit history of a building, its air leakage, glazing and insulation properties may be estimated. Likewise, knowledge of a building's use will enable the occupant behaviour and internal loads to be estimated. If we know the physical form of a building then we can estimate its volume and wall/floor area ratio, and if we know a building's construction date, region, retrofit history and use, we can estimate the properties of its cooling, heating and ventilation equipment, and its sustainable systems. Estimates for the building properties will be based on typical or average values obtained from building typology benchmarking studies [5,24–27].

Finally, if we assign the building properties identified to be important for energy modelling to their typology classifications via the building property subsets, we obtain our final top-down building characterisation (Fig 4). This methodology relates typological building classifications to the building properties which are most important in terms of energy performance. It can be used to simplify the description of both residential and non-residential buildings for city-scale, top-down energy modelling.
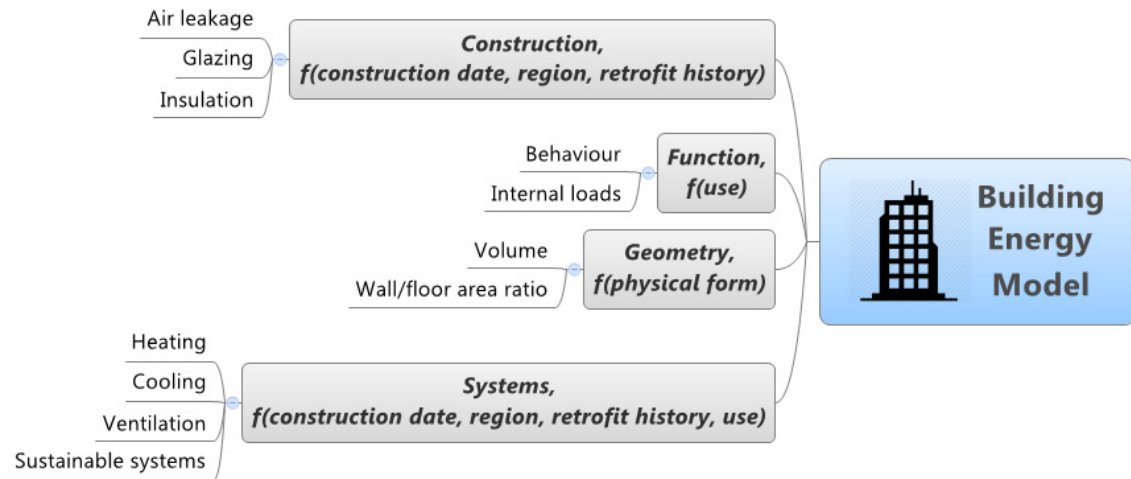
Fig 4. Final building energy characterisation.

7. Summary

Dynamic simulation tools such as INDICATE will aid the design of the smart, energy efficient and sustainable city of the future. Central to the energy performance of the city are its buildings, which will require accurate representation in the simulation tools. Existing 'bottom-up' approaches to building simulation require a large number of inputs, and high labour and processing overheads. These approaches are not suitable for models on the scale of cities when multiple buildings need to be simulated simultaneously. For this reason, a new methodology was developed for characterising the energy performance of buildings suitable for city-scale, top-down energy modelling. A review of sensitivity analysis studies was conducted to identify the building properties most important for energy modelling. These properties were then related to typological building classifications via the four building property subsets of *construction*, *function*, *geometry* and *systems*. The methodology simplifies the description of buildings in energy models and will drastically reduce labour and processing overheads.

Acknowledgements

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