LAND USE TYPE ALLOCATION INFORMED BY URBAN ENERGY PERFORMANCE: A USE CASE FOR A SEMANTIC-WEB APPROACH TO MASTER PLANNING

A USE CASE FOR A SEMANTIC-WEB APPROACH TO MASTER PLANNING

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Abstract. Cities are growing fast and facing unprecedented challenges as urban populations grow and resources are becoming scarce. A city's master planning involves a series of decision-making processes and requires knowledge from various domains. Urban planners are seeking computational support. We present a use case of land use type or building function allocations informed by urban energy performance as a pilot demonstrator for a semantic-web approach to these challenges. The software used for energy performance assessment was the City Energy Analyst. Using a quarter in downtown Singapore as an example, the results indicated 70% to 80% residential supplemented by other land use types favours efficient use of district cooling systems and photovoltaic panels. Urban planners may use the results to narrow down the search space of land use type ratios for the selected mixed-use area in Singapore. The use case serves as a pilot demonstrator for a broader research scope, the project Cities Knowledge Graph. To support master planning, the project aims to build an extendable plat-form to integrate more datasets and evaluation software for various urban qualities and domains.

Keywords. Urban planning; knowledge graph; City Energy Analyst; simulation; energy-driven urban design; urban form.

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1. Introduction

Urban areas and populations keep growing with no sign of slowing (United Nations, 2018). Urban planning is experiencing unprecedented challenges. For example, cities are responsible for approximately 75% of the primary energy use and 60% of the greenhouse emissions globally (UN-Habitat, 2012). Buildings are one of the main energy-use sectors of cities. Recent studies show that energy considerations should be integrated into multiple stages of an urban project, as early as the master-planning stage (Shi et al., 2020). Land use type allocation is one of the main tasks in a city's master planning, and it defines the buildings' functions or land use types in each block.

Land use type allocation, and master planning in general, involves a series of decision-making processes. Planning cities draws on transdisciplinary approaches of knowledge formation across various disciplines (von Richthofen, 2018). Growing proliferation of data and increasing computational power offer unprecedented possibilities for future planning tools (Batty, 2018). However, computational tools from different domains are usually developed and executed independently. As the aim of master planning is to develop a coherent synthesis between inputs and needs from different domains, there is a challenge to ensure the interoperability of domain-related tools and respective datasets. Semantic Web Technologies can be used to link data across domains and to tackle various aspects of urban planning (Gomes et al., 2012).

2. Background: the Cities Knowledge Graph Project

The present paper reports on work done as part of a multi-year research project that develops approaches to computationally support multi-domain interoperability and synthesis in city planning. The 'Cities Knowledge Graph (CKG)' project (Cities Knowledge Graph, 2021), which started in April 2020, applies semantic web technology to develop a pilot planning support system to help bridge gaps between individual knowledge domains (such as energy, mobility, or built form), supporting planners in synthesizing that knowledge into an integrated view of the future city. The CKG is an effort which brings together existing expertise on knowledge graph platforms (Eibeck et al., 2020) and city planning (Cairns and Tunas, 2019). The project's core aim is to demonstrate the potential of semantic web technology for city planning support, building on an understanding of prior work and research gaps in the domain of semantic city planning support (von Richthofen et al., 2021) in order to develop particular innovations. A key innovation is the ability to generate various alternative scenarios (called "parallel worlds") to represent cross-domain city planning scenarios or digital twins of cities (Eibeck et al., 2020). CKG is part of a larger endeavour of knowledge modelling called the World Avatar (Menon et al., 2019; Pan et al., 2016; Zhou et al., 2018).

The architecture of the CKG platform is a combination of a back-end system (knowledge graph platform) and a front-end interface to collect requests from urban planners. This work presents a pilot use case as the first exploration for the CKG platform. The layered architecture of this system works as follows. First, we build on a collection of 'common languages' (i.e. ontologies) that describe concepts and their relationships for different knowledge domains used in planning. In the use case, we demonstrate relating the concepts used in master-planning (i.e. land use) to those in urban building energy modelling (i.e. occupancy). Second, we use these ontologies to create a linked network (i.e. a semantic web) of knowledge domains, data related to these domains, and even software used by these domains. In the use case, we demonstrate linking the datasets acquired from the planning authority's open database and those for energy simulations. Third, we incorporate artificial intelligence, in the form of agents that work on the knowledge graph to better control information flows (to automate information retrieval or data conversion, operate software, or generate visualizations); answer multi-domain queries; and recognize new patterns and infer master-planning knowledge. In the use case, we pilot the processes of controlling the information flows by creating a series of possible planning scenarios, conducting assessment, reasoning for master-planning knowledge and generating output diagrams.

3. Method

In the use case, we aim to determine the ratios of these use types in-formed by urban energy performance. As an example, we use a quarter of downtown Singapore, where most of the street blocks are planned yet vacant. Figure 1 illustrates the area in the Singapore Master plan (Urban Redevelopment Authority, 2014). The gross plot ratio of each street block is defined, and the land use is colour-coded as white, which allows a combination of up to nine use types, including residential, office, shop, hotel, serviced apartments, recreation club, association, convention or exhibition centre, or entertainment. Different land use type mixes entail different performance or efficiency of the energy supply systems (Shi et al., 2017). In this example, we assume the district's cooling demand is serviced by a district cooling system (DCS), and the district's total electricity demand is supplied by electricity generated by building-integrated photovoltaic panels (PV) as an addition to the city electricity grid.

Figure 1. The selected area in downtown Singapore in the Singapore Master Plan.

Figure 2 illustrates our workflow. The methodology is structured according to four actions of master-planning. In the CKG, planning actions performed by the platform's multi-agent system are categorized as either Representation, Evaluation, Creation, or Knowledge Management actions (von Richthofen et al., 2021). The Knowledge Management action collects the required site data for the creation of planning scenarios (Section 3.2.1), executes data format conversions (Section 3.1.2), and conducts results analysis and reasoning in Section 4. The Creation action uses a parametric model to generate different scenarios of use type mixes based on the experimental design in Section 3.2. These design scenarios are assessed by Evaluation for their energy performance using the City Energy Analyst (CEA), an open-source toolbox for urban building energy modelling (The CEA team, 2020) (Section 3.3). The action of Representation is reflected throughout the three-step method and the results.

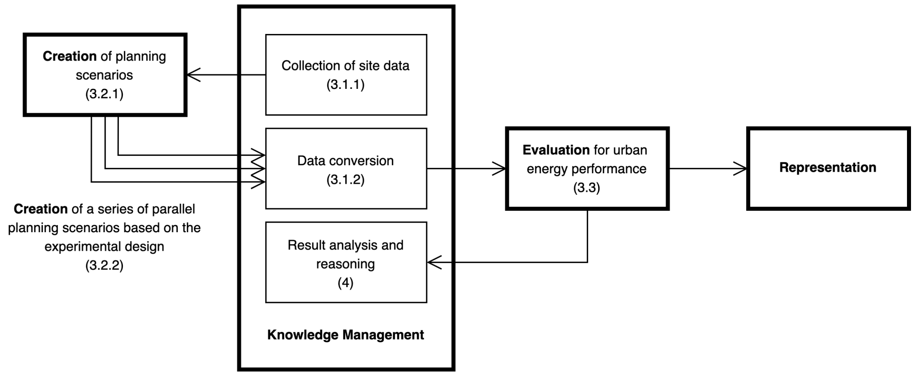

Figure 2. The workflow of the use case and the corresponding actions of master-planning.

3.1. KNOWLEDGE MANAGEMENT

3.1.1. Site data

We acquired the site data for the creation of various planning scenarios of land use type allocations from Open Street Map. Modifications were made based on the Singapore Master Plan, which is available at URA Space operated by Singapore's planning authority (Urban Redevelopment Authority, 2014). The site data includes street centerlines and borderlines of each street block in shapefiles, and the plot area ratio of each street block. Other input parameters were retrieved from the literature of existing studies of high-density areas of Singapore. Details can be found in Section 3.2.1.

3.1.2. Data conversion

The 3D city models produced in the Creation of planning scenarios are converted to the format required for City Energy Analyst. Figure 3 presents the UML (Universal Modeling Language) class diagram of these inputs' features and formats.

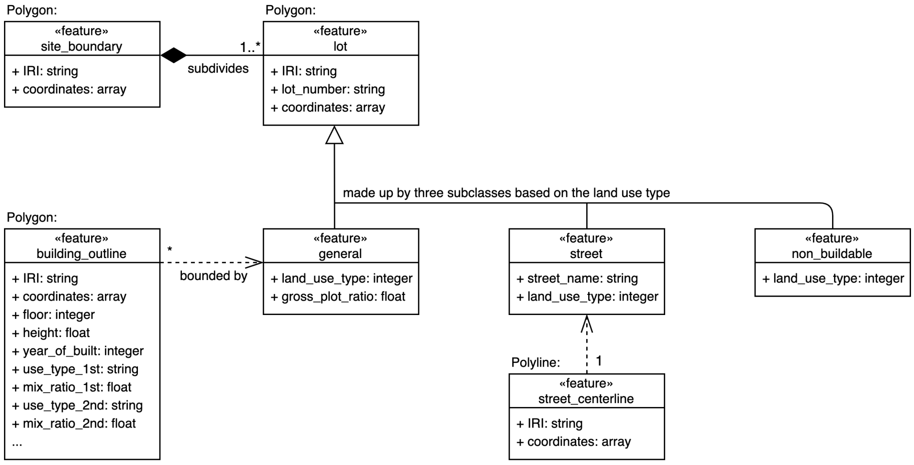

Figure 3. The UML class diagram of the master-planning ontologies used in this work. The selected area is subdivided into lots, which consist of three subclasses based on the land use type, including general plots, street plots, and non-buildable plots like water-bodies. Building outlines are bounded by general plots. Each item of the features is defined based on an open data platform of Singapore's planning authority named URA Space, comprising datasets across governmental sectors (Urban Redevelopment Authority, 2014). In addition, the use of IRI (Internationalized Resource Identifiers) helps identify and link the data point.

3.2. CREATION OF PLANNING SCENARIOS

3.2.1. Land use type allocations

The selected district contains 35 street blocks, 30 of which are planned using a gross plot ratio, which sets the maximum amount of allowable built area on a particular plot as a ratio to the plot's surface area). The five remaining vacant street blocks either are envisioned as open spaces or contain conservation buildings. Each block has one building, and the site coverage is set at 0.47. Each building's footprint follows a podium building pattern, which is offset by the block's borderline (Shi et al., 2020). Figure 4(a) shows 3D geometries conforming to the maximum planning settings above. Some of the nine land use types under the white-colour code have similar characteristics of energy use, in terms of occupancy and schedule. For simplification in this first-step demonstrator, we group similar ones. Thus, the number of use types is reduced to five, including residential, office, shop, exhibition, and entertainment.

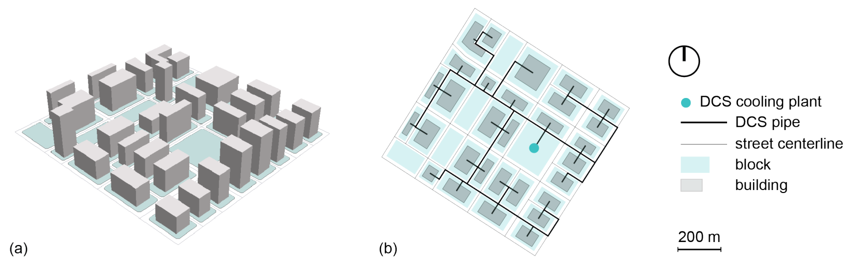

Figure 4. (a) the 3D scenario of master-planning made in Creation; (b) the piping network layout used in all samples.

3.2.2. Experimental design

To explore the impacts on urban energy performance of various ratios of the five defined use types, we try to evenly distribute the sampled da-ta point of the ratio of each use type and exhaust their combinations. We follow two steps. First, we group all thirty buildings of the district into ten groups of approximately the same gross floor area. The grouping only considers the gross floor area as a recent work indicates the impact of buildings' spatial locations on DCS's efficiency is relatively insignificant (Shi et al., 2021b). Second, we assign one of the five use types to these ten groups. Each group can only have one use type. Together, the ten groups can feature one, two, three, four, or all of the five use types. In this way, there are 1001 scenarios of various use type allocations. The ratio of each use type can be 0% to 100%, with a step of 10%.

3.3. EVALUATION FOR ENERGY PERFORMANCE

We use the City Energy Analyst (CEA) v3.13 (The CEA team, 2020) to simulate building energy demand (Section 3.3.1), PV electricity yields (Section 3.3.2), and district cooling system design and operations (Section 3.3.3). The metrics for assessing the energy performance are explained in Section 3.3.4.

3.3.1. Energy demand

The energy demand simulations are conducted for each scenario created in the previous section. The inputs comprise the building geometries, the occupancy profiles based on the land uses, and the energy supply-related data. These data, including the temperature set points, the ratios of air-conditioned area, the HVAC (Heating, ventilation, and air conditioning) technology selections, and building envelope properties, and the Singapore weather conditions, are available in the CEA database (The CEA team, 2020). CEA adopts occupancy schedules adjusted to Singapore conditions based on the ASHRAE standard schedules. The simulation outputs include hourly demand for space cooling, electricity for appliances, and domestic hot water in kWh. CEA converts these three types of energy demand into a single metric: total electricity demand from the city grid.

3.3.2. Photovoltaic panels

CEA simulates the photovoltaic (PV) electricity yields based on the results of a validated solar radiation simulation tool named DAYSIM (MIT Sustainable Design Lab, 2020). The shading effects of building geometries are accounted for. The results of the solar radiation simulations are also used in the energy demand simulations for solar heat gains. Based on a recent study in Singapore (Shi et al., 2021a), the annual solar radiation threshold for installing PV panels is set at 800 kWh/m2. The PV panel type used in the simulations is generic monocrystalline panels with a nominal efficiency of 0.16. The output is hourly PV electricity yields in kWh.

3.3.3. District cooling systems

We assume all the buildings within the district are serviced by a single-plant district cooling system (DCS). Figure 4(b) presents the DCS cooling plant integrated with the transit station, the piping network following the street layout, and buildings connected at the centroid of the building footprint in the CEA simulations. The pipe insulation is made of polyurethane, and its thermal conductivity is 0.023 W/mK. The supply temperature of the chilled water from the DCS cooling plant is ˜5.4 °C, and the plant COP (coefficient of performance) is ˜4.4. The choice of DCS technology remains the same in all iterations. The DCS cooling plant consists of vapour compression chillers and cooling towers. The outputs of the CEA simulations include the sizes of these DCS components, determined by the peak cooling demand and the thermal loss in the piping network. As the cooling demand fluctuates over time, the DCS does not function at its maximum at all times.

3.3.4. Assessment of urban energy performance

The metrics used for assessing the energy performance of the PV panels and the DCS are selected based on two recent studies (Shi et al., 2020, 2021). For PV panels, the metric used is solar energy penetration calculated as:

$$\text{Solar energy penetration} = PVel/ELgrid[-](1) \qquad (1)$$

where PVel is the annual PV electricity yield in kWh; ELgrid is the annual total electricity demand from the city grid in kWh when no PV panels are installed. Higher solar energy penetration indicates higher integration of on-site solar energy into the electricity supply mix. For DCS, the metric is chiller capacity factor, which measures the utilization of the chillers throughout a year. It is calculated as:

$$\text{Chiller capacity factor} = Qc/Qs, nom[-](2) \qquad (2)$$

where Qc is the annual cooling energy supplied by the DCS in MWh; Qs, nom is the annual cooling energy that the chillers in the DCS cooling plant can supply in MWh, provided they functioning at their nominal capacity. Higher chiller capacity factor indicates more efficient DCS.

4. Results

Figure 5(a) presents the results of our energy performance assessment for the 1001 planning scenarios of various land use type allocations, by their simulated chiller capacity factor and solar energy penetration. The scenarios in the top 20% of solar energy penetration show a broad range of performances on chiller capacity factor and vice versa. There are 22 planning scenarios that are in the top 20% for both energy performance metrics. Figure 5(b) presents the ratios of land use types for these 22 planning scenarios (vertical bars). The majority have 70%˜80% residential use. On one hand, high residential ratios necessarily imply high solar energy penetration, as residential use has a lower energy intensity than the other land uses (photovoltaic electricity yield is the same for all 1001 planning scenarios, as all scenarios feature the same built form). On the other hand, during the daytime, the negligible (solar) energy use of mostly absent residents is supplemented by the cooling demand of other land use types. Hence, despite solar energy penetration favouring residential use, up to 30% of other uses leads to more optimal land use type allocation scenarios, as these scenarios feature high chiller capacity factors, as they reduce the number of idle hours of the district cooling plant.

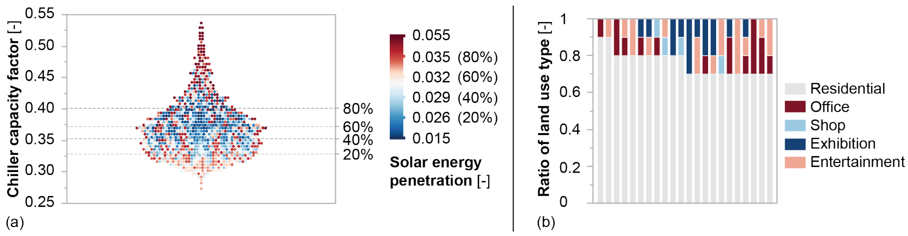

Figure 5. (a) The energy performance is assessed for the 1001 planning scenarios. The chiller capacity factor and solar energy penetration are displayed by the y-axis and the colour gradient. 5-quantiles are observed. (b) The ratio of land use type of the 22 planning scenarios (vertical bars) performing top 5% on both solar energy penetration and chiller capacity factor.

5. Discussion

The use case presented above will be part of a pilot demonstrator for the Cities Knowledge Graph (CKG) project. In this demonstrator, an urban planner uses an interface to raise the question: "In the selected mixed-use district, how do different ratios or combinations of land use type influence district energy performance?" After querying relevant datasets, conducting (CEA) evaluations, and reasoning, the CKG platform would return the needed knowledge of master-planning to the planner as represented in Figure 5 (b). Such energy-driven knowledge helps narrow down the design space for land use type allocation.

Keeping in mind the broader framework in which the presented use case will function, there are three main limitations and challenges of the present paper. Firstly, on the topic of simulation accuracy, the building geometries produced in the action of Creation are simplified as boxes, which affects the accuracy of electricity yield simulations, due to shading effects. Ideally, in future, the level of details of future 3D city models should be scalable, according to the respective master-planning questions. Similarly, for the accuracy of the energy demand simulation, specific occupancy data for each land use type should be used. Secondly, considering the practicality of the simulation, we should note the computational expense of the use case is high (CEA simulations require high computational power). At a project level, we should consider integrating alternative simulation software and experimental design methods, so we can adapt accuracy and computational expenditure depending on the planning task. Thirdly, the presented use case of course demonstrates but two aspects of an energy performance assessment. Simulations could take into account many more criteria that affect district-scale energy performance, as well as other domains (such as mobility, pollution, and outdoor thermal comfort) that introduce different or even contradicting parameters to determine land use type allocation.

Exploring how to support such complex planning interactions is a main aim of the CKG project, linking available cross-domain multi-scale urban datasets and respective evaluation software to support the decision-making processes of master-planning. The presented use case is the first step in this exploration.

6. Conclusions

In this paper, we have presented a pilot use case of land use type allocations informed by urban energy performance using a semantic-web approach. The metrics of solar energy penetration and chiller capacity factor are used for assessing the energy performance of photovoltaic panels and district cooling systems. Based on the experimental settings in this work, it is advised the residential use type should be kept 70%-80% supplemented by one or two or three use types of office, shop, exhibition, and entertainment. Urban planners may use the results to narrow down the search space and make decisions for the ratios of mixed-use projects. Furthermore, this work builds towards a pilot demonstrator of a broader research scope - the Cities Knowledge Graph (CKG). The pilot use case demonstrated CKG's threefold approach of relating concepts, linking datasets from various domains involved in master-planning as wells as automation of planning scenario generation, assessment, reasoning and visualization. CKG seeks to automate these processes and offer cross-domain master-planning support through a user interface to interact with urban planners. Also, CKG aims to integrate additional datasets and software of various urban planning related domains, beyond energy, using a semantic-web approach.

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