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An Innovative Tool for Optimised Development Envelope Control (DEC) Analysis and Scenario Building in Digital Twin

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ABSTRACT:

Despite the advancements in Planning Support Systems (PSS), Geographical Information Systems (GIS), and multi-dimensional building and city modelling, we found that they are not within the factual urban planning and design practice and often do not generate expected knowledge and wisdom. In addition, there is limited application of computational generated data and visualisation in the current statutory and strategic planning processes. For example, the planning and design rules and guidelines for a compact city development need to be examined and communicated to the professionals and the community to ensure that they are fit for purpose and address the users requirements. However, the planning rules are communicated through texts and diagrams, which are very difficult to understand and there is a risk of misinterpretation, uncertainty, and dissatisfaction in urban development processes. This research leverages the emerging technologies such as Digital Twin to develop a scenario-based PSS to consider the planning controls protecting the public's interest while optimising economic and spatial yield.

1. INTRODUCTION

One of the significant challenges in compact city development is evaluating the impact of design and planning rules on new building developments in inner cities. Planners are interested in understanding the city's capacity in terms of physical, environmental, and economic aspects for sustainable development. However, answering the question of how much more compact development can we sustain or modify in a neighbourhood area remained unanswered.

Furthermore, one of the critical urban planning challenges is when the design requirements need to be translated into policy. For example, in Australia, the Victorian planning scheme set design parameters for development on a land lot. According to the Victorian Planning Scheme, "these design parameters can be described by diagrams, plans or written descriptions, or a combination of both." However, the two-dimensional plans and diagrams, and written policies can be easily misinterpreted due to the lack of digital representation of design parameters (Figure 1).

While the advancements in Geographical Information Systems (GIS) and parametric design capabilities enabled the urban designers and planners to better design evaluation, there are some limitations in the current tools (Agius et al., 2018). There is a lack of scalable automating workflow of the 3D building models based on rules and associated features such as road type, width, and open spaces. This research aims to develop a Planning Support System (PSS) to consider the planning controls protecting the public's interest while optimising economic and spatial yield.

2. LITERATURE REVIEW

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al., 2009) approach was adopted in conducting the literature review. Scopus and Web of Science databases were searched for eligible studies. Searches through February 2022 were conducted with the English language and no publication date as restrictions. The following keywords were applied to the search: (building envelope) AND (3D) AND (urban development). The next step was removing duplications and screening the metadata in each database. The screening process involved filtering the literature based on the relevancy of the subject category to the study's scope, language

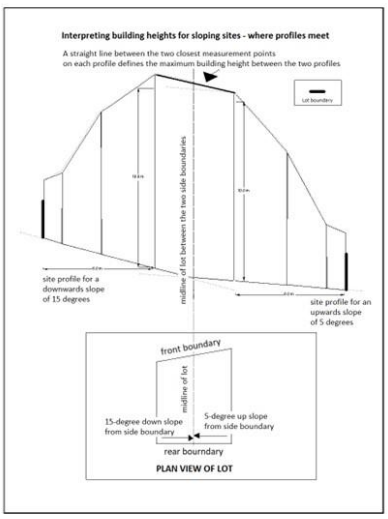

Figure 1. Interpreting building heights for sloping sites. Source (Department of Sustainability and Environment, 2003)

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(English only), and document types (only articles and book chapters included). As a result, a total of 202 documents out of 31,466 were retrieved from the two scientific repositories. Among the 202 documents, 188 are from Scopus, and 14 are from Web of Science.

The next step is identifying duplication in two databases and filtering based on their eligibility to be considered in this study. As the eligibility criteria, the literature should address an urban planning or policy issue (environmental, economic, social), using a decision support system for decision making. In addition, only empirical studies were included in the final list. Therefore, using the selection criteria and duplication check, 23 scholarly articles were selected for analyses in this study. The literature is then categorised into three groups: application, impact, and data types (spatial and 3D).

From the application perspective (Table 1), most studies focused on urban and buildings' energy and environmental analysis. One of the significant applications of 3D modelling in urban planning is the thermal energy performance of buildings. This is important from two points of view. First, understanding the implication of buildings' energy performance on urban heat island mitigation measures is an important task for urban planners and urban designers (Bozonnet et al., 2015). Second, using renewable energies such as solar power is considered one of the strategic planning milestones to address low-carbon emissions and climate adaptation (Lindberg et al., 2015). Despite the value environmental, social, and economic values communicated through the literature, an end-to-end automation process for digital assessment methods is lacking in the state-of-the-art.

Domain	Detail	Literature
Solar Energy	Solar Farming in Urban areas (PV)	(Zhu et al., 2022)
	Solar rights/overshadowing	(de Luca and Dogan, 2019; Shach-Pinsly and Capeluto, 2020; Stasinopoulos, 2018)
	Solar irradiation estimation	(de Luca, 2017; Lindberg et al., 2015; Zhu et al., 2020)
Building Energy	Energy performance of buildings (Thermal)	(Bozonnet et al., 2015; Cheng et al., 2018; de Trocóniz y Revuelta et al., 2013; Elbeltagi et al., 2017; Keller et al., 2018; Martín-Consuegra et al., 2018; Mastrucci and Rao, 2017; Mutani et al., 2019; Mutani and Todeschi, 2021; Tooke et al., 2014; Yi, 2015)
	Building energy retrofit modelling	(Rogeau et al., 2020)
Air Quality	Trees Pollen Concentration	(Fernández-Rodríguez et al., 2018)
	CO2 emissions	(Cheng et al., 2018; Soust-Verdaguer et al., 2018)
Rainwater management		(Bozonnet et al., 2015)
Noise map		(Tisseyre, 2014)

Table 1. Application domains of 3D city and building models in urban planning.

The literature on the solar analysis used the buildings and development envelope to measure the solar irradiation (de Luca, 2017; Lindberg et al., 2015; Zhu et al., 2022, 2020), solar rights, and solar harvesting (de Luca and Dogan, 2019; de Luca, 2017; Shach-Pinsly and Capeluto, 2020; Stasinopoulos, 2018). Furthermore, the literature suggests that building energy modelling should be analysed in different scales such as urban and neighbourhood levels (Bozonnet et al., 2015; Cheng et al., 2018; Keller et al., 2018; Martín-Consuegra et al., 2018; Mutani et al., 2019; Mutani and Todeschi, 2021; Tooke et al., 2014). One of the critical applications of 3D building/city models is lifcycle assessment (building design, development, implementation, performance, retrofit, and demolish) (de Trocóniz y Revuelta et al., 2013; Elbeltagi et al., 2017; Mastrucci and Rao, 2017; Saroglou et al., 2017; Soust-Verdaguer et al., 2018; Yi, 2015).

It is also important to evaluate the impact of urban development using 3D models. The literature can be categorised into the environmental, economic, and planning regulation groups (Table 2).

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Domain	Detail	Literature
Economic	Urban energy costs	(Bozonnet et al., 2015; Cheng et al., 2018; Zhu et al., 2022)
	Retrofit cost optimisation	(Rogeau et al., 2020)
Environmental	Building energy	(de Trocóniz y Revuelta et al., 2013; Elbeltagi et al., 2017; Keller et al., 2018; Martín-Consuegra et al., 2018; Mastrucci and Rao, 2017; Mutani et al., 2019; Mutani and Todeschi, 2021; Tooke et al., 2014; Yi, 2015)
	Solar volume (SV)	(de Luca, 2017; Shach-Pinsly and Capeluto, 2020; Stasinopoulos, 2018)
	Sollar irradiation on the urban scale	(Lindberg et al., 2015; Zhu et al., 2020)
	Air quality	(Cheng et al., 2018; Fernández-Rodríguez et al., 2018; Soust-Verdaguer et al., 2018)
Planning Regulations and Guidelines	Solar collection envelope (SCE) and Solar rights envelope (SRE)	(de Luca, 2017; Shach-Pinsly and Capeluto, 2020; Stasinopoulos, 2018)
	Noise impact assessment	(Tisseyre, 2014)

Table 2. Impact analysis of the 3D city and building models in urban planning.

Urban energy cost is important for homeowners, developers, and urban policy makers. While several building energy modelling tools are available in the market, there is a disconnection between the design and planning and building/urban energy evaluation processes. There is also a growing attention to the developing urban planning regulations and guidelines from use cases such as solar collection envelope (SCE), solar rights envelope (SRE), and noise, which depict the importance of 3D data analytics (de Luca, 2017; Shach-Pinsly and Capeluto, 2020; Stasinopoulos, 2018; Tisseyre, 2014). However, most of the current analytics remained at 2D level. One of the challenges of this limitation is the lack of 3D data. As Table 3 demonstrates, most of the data is in 2D format (Keller et al., 2018) or 3D non-spatial models (3D architectural design) (de Luca, 2017).

Application Domain	Detail	Literature
3D Model	3D Point Cloud	(Cheng et al., 2018; Lindberg et al., 2015; Tooke et al., 2014; Zhu et al., 2022, 2020)
	3D Architectural Design	(de Luca, 2017; Shach-Pinsly and Capeluto, 2020; Tisseyre, 2014)
	CityGML, 3D Cadastre	(Mutani et al., 2019)
	Building Information Modelling (BIM)	(Fernández-R (Fernández-Rodríguez et al., 2018; Sabri et al., 2019; Soust-Verdaguer et al., 2018)
	2D extrude	(Keller et al., 2018; Martín-Consuegra et al., 2018; Stasinopoulos, 2018)
Building Material and Land Cover	Building Energy Certification data	(Mutani and Todeschi, 2021)
	Building stock information	(Elbeltagi et al., 2017; Rogeau et al., 2020; Saroglou et al., 2017)
	Urban databanks (2D)	(Bozonnet et al., 2015)
GIS (attributes)	Height, construction year, Surface/Volume ratio, user types, weather station data, heating information	(Mutani et al., 2019)
Assumptions based on jurisdiction and reference data	Reference net floor area in India (Carpet area)	(Mastrucci and Rao, 2017)
User input	Layout generation in 2D	(Yi, 2015)
Remote Sensing data	Digital Surface Model (DSM)	(Lindberg et al., 2015)

Table 3. Spatial and 3D data types that used for the city and building models in urban planning.

The analysis of the current studies shows that there is a focus on the existing urban morphology, buildings, and their solar irradiation and energy performances (de Luca & Francesco, 2017; Zhu et al., 2020). The evaluation of building design performance for energy consumption has been another line of research (de Luca & Dogan, 2019; Stasinopoulos, 2018).

In 2020, an empirical study (Shach-Pinsly & Capeluto, 2020) developed a performance-based code (PBC) to introduce the building performance evaluation in the planning process. The authors argued that transforming from form-based code (FBC) to

PBC will improve the planners' understanding of building performances such as solar envelope and security index. However, the security index analysis is based on 2D data and the proposed solar envelope calculation is based on single architectural building designs examined in the existing built areas of cities. The literature, however, lacks the auto-generated building envelope based on the planning rules.

Furthermore, Geertman, (2006) argued that most of Planning Support Systems (PPS) are not within the factual planning practice and often do not generate expected knowledge and wisdom. For example, there is a lack of integrating other urban features such as road network, open spaces and green spaces as influencing factors in empirical works in optimum building yield for a wholistic sustainable compact city development. In addition, the analysis of literature in this study highlights the lack of application of computational generated data and visualisation in the planning process, confirming the challenge that Punt et al. (2020) outlined for the current PSS.

3. METHODOLOGY

In this work, we propose and implement an innovative framework for development envelope creation and analysis using parametric design and GIS techniques deployed on the Digital Twin as a PSS platform. The framework demonstrates a methodology that starts with 2D polygon geometries and user-defined creation rules and constraints to control the generation of 3D development envelopes. The process is initialized on the front-end application by applying the rulesets and estimating simplified envelopes with spatial analytical methods; then generated 3D envelopes will be stored on a 3D geospatial database (PostgreSQL+PostGIS) in polyhedron surface format which can be further used for conducting floor-level analysis and visualisation. It is important to note that, this framework is formulated for more than a building to support the planning and decision-making for a neighbourhood or urban block development. Therefore, we decided to use "Development Envelope" instead of "Building Envelope" in this work.

The workflow for the development envelope control creation logic is illustrated in Figure 2, and the key processing steps for each envelope is also attached at the bottom of Figure2. The implemented framework includes a three-level control hierarchy for the generation of development envelopes which are: (1) envelope level, (2) edge level, and (3) vertex level whereby the vertex level is the highest. Each level enables different modelling capabilities where more editing controls becomes available as it moves from envelope level up to vertex level. It is worth mentioning that the hierarchy must be respected whereby prior to getting on the vertex level, it is required to progress systematically from the envelope and then the edge level first. The violation of this hierarchy will cause the envelope to regress back a step down of the hierarchy, losing the parameters set for the one above.

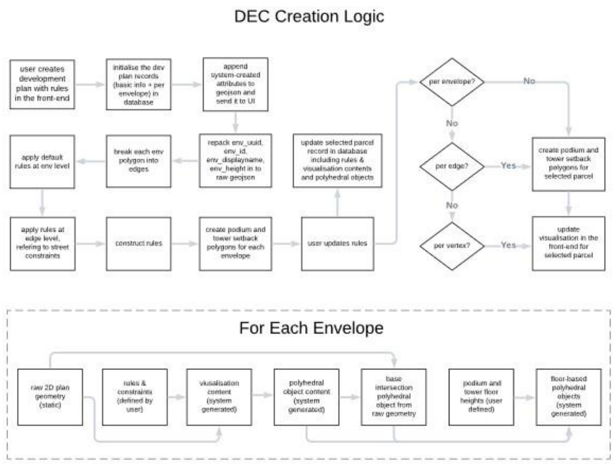

Figure 2. The overview workflow for Development Envelope Control creation. The key processing steps for each envelope is described at the bottom.

3.1 Development Footprints

The primary dataset crucial for this tool is 2D development footprints. This dataset can be acquired from planning framework plans that illustrate high-level objectives for the maximum extent each building is allowed to build up to. Information such as maximum height and setbacks will benefit in the forefront however, they can be viewed as secondary importance due to the purpose of the tool that is to test existing or trialling of new design controls. Nevertheless, the dataset must contain predefined maximum height, unique feature identifier and feature name to begin with. It is also crucial to note that these 2D development footprints should comprise generic geometry shapes and should avoid complicated edges in any case. This is because a development footprint is dissimilar to a building footprint where detail outlines are not the priority and will only increase processing time and extra parameters to edit which can be time-consuming.

Additional datasets such as roads, open space and like can be sorted after to be used as constraints to further assist in the automation of generating envelopes. This is significant as the intention of applying design controls onto buildings are used to protect the interest of the public, safety and privacy. Therefore, by allowing the system to recognise these features during the process of envelope generation, these constraints can be incorporated at the early stage of it. Besides that, these features should contain attributes that categorise the level of importance for the system to determine the type and number of constraints it is going to assess. For this study, the feature road dataset with four different classes will be demonstrated (Figure 3).

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Figure 3. An example of development footprints (the blue polygons).

3.2 Control Ruleset

There are two approaches to applying the ruleset onto the generation of the envelopes which are: (1) predefined ruleset from the database and (2) on-the-run parameter assignment. The selection of a predefined ruleset will enable the automatic assignment of appropriate parameterisation for each design control. Conversely, design control parameters can be manipulated on the run if the predefined ruleset is absent. Constraints feature datasets, in this case, the roads, is required to have attributes that consist of ordinal classes for the system to assign them into a hierarchy of dominance. In developing the rulesets, we considered two specific levels of buildings, which are podium (or ground level), and top (or upper ground levels) (Figure 4).

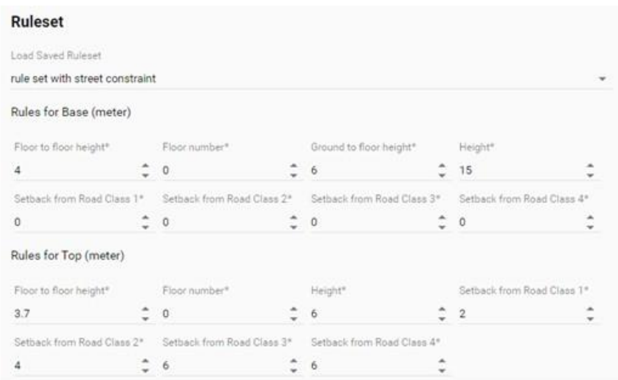
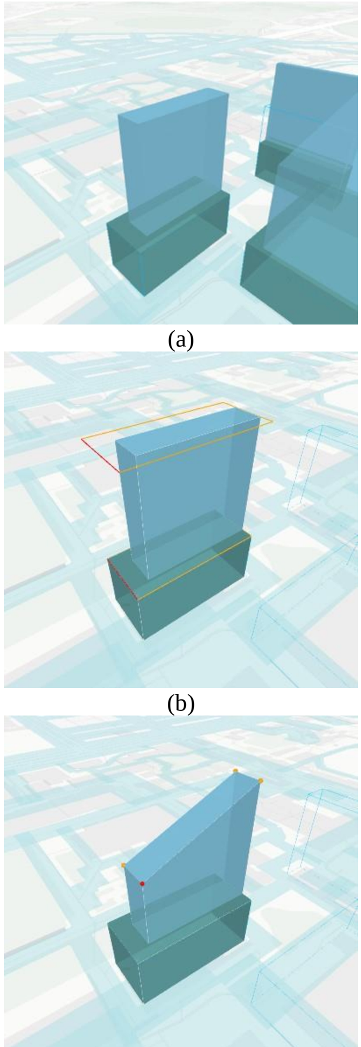


Figure 4. User-defined ruleset for both base and podium (top). Floor heights, floor numbers, setbacks are treated as rules at envelope level; setback rules can be applied at edge level and the height can be further applied at vertex level.

3.3 3D Development Envelope Generation and Visualisation

By using user-provided development footprints and control rules, the system can automatically create 3D development envelopes which respect all the rules and constraints. It also offers users the flexibility for manually modifying the generated envelope at any of the three-control hierarchy levels. The visualisation (Figure 5), envelope statistics will be updated in real-time when manual changes apply. Users can also define the rendering colors based on floor attributes such as height.



(a)

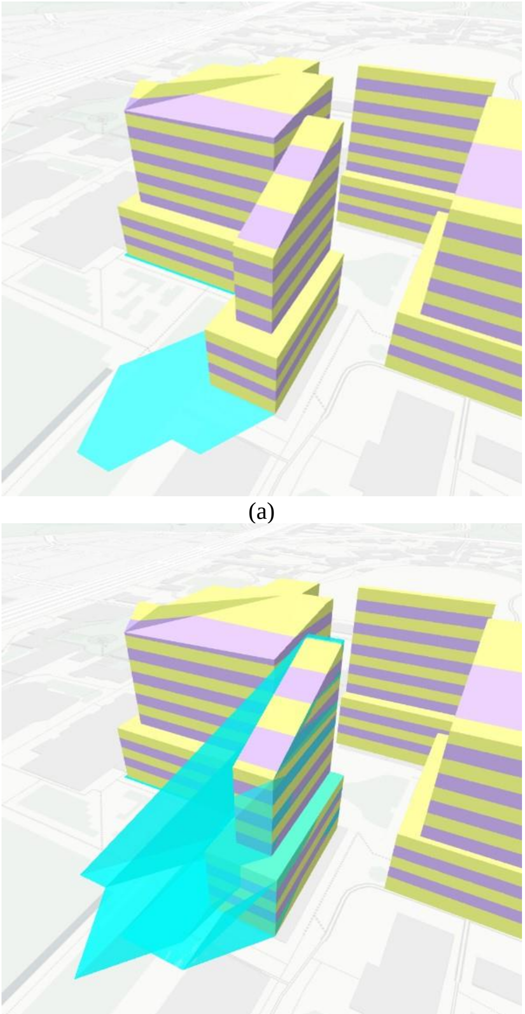
(b)

(c)

Figure 5. Generated 3D development envelopes, users can further modify rules at (a) envelope (b) edge (c) vertex levels and the visualisation and calculation will update in real-time.

3.4 Spatial Analytics

A suite of key analytic properties is computed for every envelope successfully generated in the system such as gross floor area, floor area ratio, maximum and optimum capacity as well as envelope discrepancy. This statistical information is crucial to understand the implication in terms of yield for the ruleset applied onto the development footprint. Conversely, the tool has also integrated 2D and 3D shadow analysis to assess and quantify solar access to the surroundings of the building envelopes.



(a)

(b)

Figure 6. 2D (a) and 3D (b) time-series shadow analysis results and visualisation.

4. RESULTS AND DISCUSSION

The implemented Development Envelope Control framework has successfully achieved the following key features:

- Create new development envelope control and define default rulesets and constraints including corridors rules.
- Support three hierarchy level of ruleset constraints include envelope level (height constrains, number of floors, setbacks), edge level (setbacks), vertex level (vertex height).
- Evaluate rule-based development plans by generating 3D development blocks with statistics includes total lot area, number of floors, top area, envelope height, envelope discrepancy area, total gross floor area, floor area.
- Generate single or animated 2D & 3D shadows from selected envelopes and also highlight the shadow impacted development envelopes.
- Style the model results appearance based on the floor attributes.

The implementation of this tool demonstrates a dynamic way for practitioners to test and visualise the result of planning controls assigned to building developments and shows that multi-dimensional design parameters can be effectively modelled and analysed by planners with low technical expertise. This capability addresses the Geertman’s (2006) argument about contributing of PSS to the factual planning process. As a result, the concern of misinterpreting design controls merely from extracting information from the written policy is addressed, improving planning workflow and accuracy. The ability to adjust design parameters and retrieve spatial analytics quickly is appealing for planners to undertake real-time workshops with stakeholders and provide several options that can best capture in protecting the interest of the public (I.e., privacy, protection or environmental).

This tool contributes to the planning support systems, by introducing a workflow that incorporates the planning regulations about building and surrounding features (e.g., road network). Furthermore, the tool enables planners and designers to modify the building envelope’s geometry (edge and nodes), which is a novel feature that has not been used in current tools. This feature supports a more sustainable planning outcome and enables the planners and designers to make an evidence-based decision for building energy and solar irradiation measures. The tool, therefore, improved the previous works (de Luca, 2017) and created a dynamic and interactive environment for scenario-based analytics. The 2D and 3D shadow impacts are not fixed for a particular daytime (de Luca and Dogan, 2019), whereas the tool enables generating the shadows for a frequency of time determined by user (every 5 or 10 mins).

From a technical perspective, the tool’s capability in generating 3D models in polyhedron volumetric geometry allows developing a robust environment for building modification and impact analysis. Furthermore, the developed tool incorporates the characteristics of other urban features including the road type in developing building envelope through spatial reasoning methods. A feature that has not been found in other available tools to the knowledge of authors.

This tool needs to be tested in different urban settings and development types. For example, the CBD high-rise buildings need further attention to the impact of shadows on open spaces. In addition, considering the natural urban features (e.g., river and vegetations) and urban infrastructure and utilities (e.g., powerline and sewerage) regulations can improve the tool. Furthermore, the tool can be improved through the adoption of machine learning methods for comprehensive and optimised building envelope generation. In terms of transferring results to other platforms and workflows, while the data formats are created based on Open Geospatial Standards (OGC), in the future we will investigate the methods of exporting 3D data and generalising the tool.

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