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# A rapid urban de-carbonization scenario analysis tool

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**Abstract**

A rapid urban de-carbonization scenario analysis tool has been developed. The tool is able to efficiently and effectively generate and populate spatially resolved large scale building scenes, to generate XML input files for the building energy simulation engine CitySim [1], to quickly modify building thermal attributes and develop and analyze de-carbonization scenarios as snapshot modifications to the building scene. The tool has been developed as a series of plugins to the Quantum Geographical Information System (QGIS) [2] application, whereby it can make use of much of the QGIS existing functionality and software libraries. A tip to tail test of the tool is performed on a basic scenario.

## 1. Introduction

### 1.1 Context

In 2015 the world's population was estimated to be 7.3 billion people, 54% of which were estimated to live in urban areas. These figures are projected to grow to 9.7 billion and 66% respectively, by 2050 [1].

As a consequence of an increasing global population and rises in the standard the living for many of these people, the material and energy flows attributed to human use are likely to increase significantly. If the global temperature rise is to be kept within its target value of 2°C by 2100, the key contributing sectors to greenhouse gas emissions by source and by end use must be examined and strategies put in place to significantly limit their contributions.

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It is estimated that buildings and the activities within them can be attributed to approximately 31% of direct global final energy demand and are responsible for around one third of energy related $CO_2$ emissions [2]. Three questions naturally arise from the previous statements with regards to mitigating future $CO_2$ emissions from the building sector. How can we modify existing urban areas, how do we design for the growth of existing urban regions and how should we go about designing completely new cities, such that global greenhouse concentrations are able to remain within acceptable limits.

Within this context we would like answers to the questions of how buildings should be spatially distributed, how individual buildings should be configured (i.e. of what materials should they be constructed, how glazed should their facades be, etc) and which energy conversion systems and storage systems should they use.

### 1.2 Previous work

There has been a range of previous work creating and modifying spatially resolved urban scenes and visualizing the outputs. Suntool [3] is one such example where buildings can be constructed by using the software's sketching tools. Building attributes are set to iDefault values from an iDefault data set. These iDefault characteristics can be over-ridden by clicking on the individual building or surface. The scene is then passed on to the solver where energy balance calculations are performed through a range of different models.

The simulation engine CitySim [4] was the successor to SUNtool, with many improvements in the models employed (such as the thermal and behavioral models) as well as the scope of functionality. Like SUNtool a GUI was developed to allow the user to select the location and climate file, select from a default set of building types and to modify the building and energy system attributes. Optimization problems on a small subset of variables (such as building height and glazing ratio) and on small scale scenes have also been performed using CitySim in conjunction with a co-evolutionary algorithms [5].

The CitySim simulation engine is capable of modelling small scale districts as well as large scale scenes. However its application to large scale scenes has been hampered because of the time costs involved in creating the initial scenes and subsequently modifying those scenes to test a range of different scenarios.

### 1.3 The need for a new tool in the context of the "Sustaining Urban Habitats Project"

It is within the context of the issues described in section 1.2 that the rapid urban de-carbonization scenario analysis tool is being developed. This tool is being designed to quickly build and populate spatially resolved large scale urban building scenes, to generate input files for the building energy simulation engine CitySim [3], to efficiently and effectively modify large scale building scenes, and to be able to analyze (spatially, temporally and by attribute type) the direct and indirect energy and $CO_2$ consequences of a chain of modification decisions which make up a scenario.

The tool is being developed as part of the "Sustaining Urban Habitats" project within the Laboratory of Urban Complexity and Sustainability (LUCAS). The project is comprised of six themes (environmental, economic, social, data, computer modelling and policy). It is tasked with defining, measuring and modelling "urban sustainability". A number of case study cities are being considered within the project which vary in spatial scale, cultural context and stages of development. The cities will be modelled from the present day to the year 2050 to shed light on transition strategies for improving their urban sustainability. A hypothetical cities model is also being developed with a number of aims. The first is to help explore which modelling strategies should be used within the integrated modelling platform which is being developed as part of the project. The modelling strategies used will depend upon the particular question and the required accuracy of the answer, the computational overheads (related to city scale) and the available data. The second aim is to explore the question of how sustainable can a city be?

The rapid urban de-carbonization scenario analysis tool will help address some of the questions posed within the environmental theme context, whilst having overlap with the computational modeling and data themes. It has been designed in a modular fashion and so is relevant to both the real and hypothetical city cases.

In the remainder of this paper we discuss the current state of the rapid urban de-carbonization scenario analysis tool (section 2), we develop on number of demonstration scenarios and display their results (section 3), we discuss the future development of the tool (section 4) and finally reach our conclusions (section 5).

## 2. The rapid urban de-carbonization scenario analysis tool

### 2.1 Overview of the tool

A rapid urban de-carbonization scenario analysis tool is being developed which has the following objectives:

- To enable the efficient creation and visualization of large scale hypothetical building scenes in which the external building geometry is specified.
- To allow building typologies to be defined, created and their characteristics stored.
- For a hypothetical or real building scene, populate the scene with building typologies and subsequently populate attribute values in accordance with the particular typology
- For a fully attributed scene generate a CitySim XML input file and execute CitySim to obtain the energy demand profiles for each building.
- To efficiently and effectively change building attribute values such that the scene can be re-simulated by CitySim.
- To enable the user to develop scenarios around a sequence of scene snap shot modifications and to analyze the direct and indirect energy and $CO_2$ consequences of these modifications (both spatially and by attribute type)

The tool is being developed by creating a range of python plugins to the Quantum Geographical Information System (QGIS) open source application. This approach has the advantage of being able to make use of existing QGIS functionality (data visualization, editing and analysis) and software libraries [6].

The decision to build the tool around the building energy simulation engine CitySim was made because of CitySim's ability to scale to city sized spatially resolved scenes. It also has a suite of existing models (radiation, building thermal, energy conversion/storage systems and behavioral) around which an extensive range of scenarios can be generated.

In the remainder of this section we examine the current state of the tool by describing each plugin in turn. As with any tool there are always many more avenues of possible development and we will touch upon these in section 4 of this paper.

### 2.2 Building Scene Generator Plugin

The Building Scene Generator Plugin has been built to address the 1st objective listed in section 2.1. The plugin allows the user to create and visualize a hypothetical building scene with a particular form. In this context by a hypothetical building scene form we mean a geometric building scene which is constrained enough to be characterized by a small number of degrees of freedom. An example of such a form is a Manhattan Grid which is typically characterized by each building having a rectangular footprint of the same dimensions, with the buildings themselves arranged in a regular grid pattern. Thus if we specify a local Cartesian coordinate system in the plane we must specify the building widths in both coordinate directions as well as the regular spacing between buildings in both of the coordinate directions. The building heights must also be specified. Ordinarily for a Manhattan grid only the building height for the characteristic building must be specified, all other buildings taking the same value. Here, and for all building scene forms, we allow the building height to be specified according to a probability mass function specified by the user. We must also specify the position and orientation of this local coordinate system with respect to a global coordinate system (for climate and radiation models at a later stage).

A Graphical User Interface (GUI) has been developed with the plugin making use of Qt designer and the PyQt libraries. This enables the user to pick from a list of existing building scene forms. A one to one mapping

between the building form list and a Qt stacked widget allows a unique set of attributes, corresponding to the degrees of freedom, to be displayed depending on the particular form chosen. Once the user has specified the particular value for each degree of freedom, the plugin creates a QGIS vector layer, with the relevant external building geometry data, and uploads this to the QGIS environment for display.

The plugin has been built in a modular fashion such that new building scene form can be added in a relatively simple way. A new page must be added to the stacked widget, within which particular values of the form's degrees of freedom can be entered. This data will be passed to a new class which specifies the geometry of the building footprints and their relative distribution
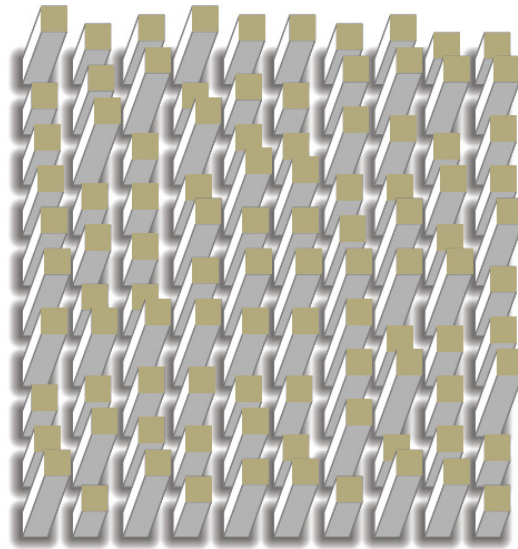


Figure 1: A Manhattan Grid scene generated in the Building Scene Generator plugin

*2.3 Building Type Generator Plugin and Distribute Types Plugin*

The Building Type Generator plugin has been designed for creating building typologies. The user is able to specify probability distributions and density functions for the sample space corresponding to a particular building attribute. The building type is then specified not in terms of absolute values of a list of attributes, but rather in terms of probability distributions and density functions for the list of attributes. Hence two building types differ by having one or more different probability distributions or density functions for the list of building attributes. For example the user can specify the probability distribution of a particular building type having double brick, clear cavity or insulated cavity walls. The sample space of wall, window, floor and roof constructions is read in from a dictionary of possible types (which are in turn linked to a dictionary of material types, with attributes of thermo-physical properties). The Graphical User Interface designed for the Building Type Generator is displayed in figure 2.

The Distribute Types plugin has been designed to distribute building types (such as those created by the Building Types Plugin) to a QGIS vector layer of building geometries (such as those created in the Building Scene Generator Plugin or imported and created from footprint and height information from OS mastermap). A GUI has been created to enable the user to specify the probability distribution by which building types will be sampled when populating the scene. Once the building type of a feature has been established, additional attributes associated with

the building are populated by sampling the distribution functions belonging to that building type.
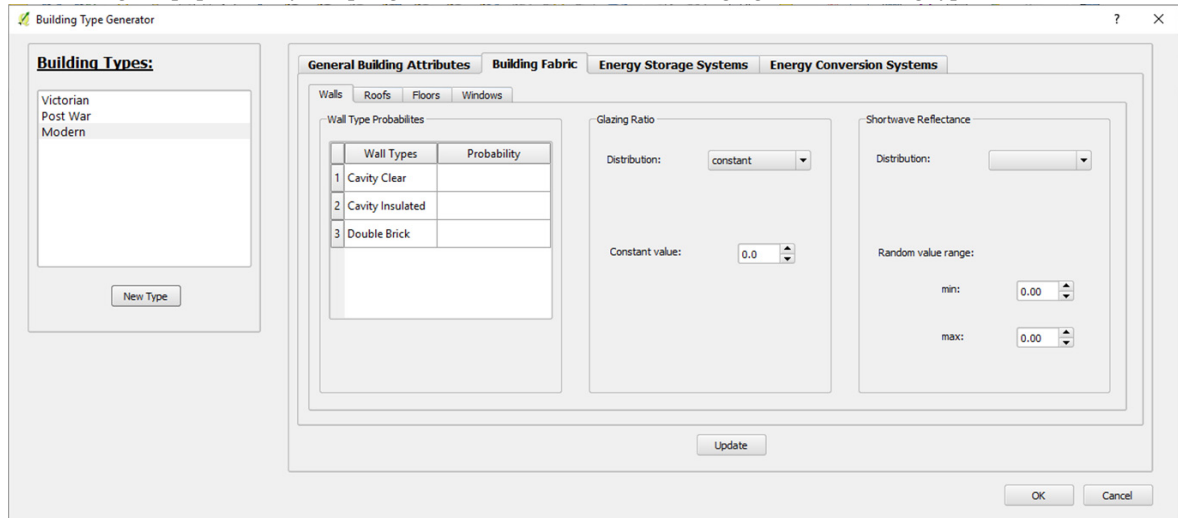


Figure 2: The Graphical User Interface developed for the Building Type Generator plugin

### 2.5 Simulate CitySim Plugin

The Simulate CitySim plugin generates a CitySim XML input file in accordance with the data stored in a selected QGIS vector layer, and subsequently executes CitySim. The QGIS layer must consist of building geometry data (such as that output by the Building Generator) and an attribute list which specifies what wall types, roof types, glazing ratios, energy conversion/storage systems, etc , are to be used (Such as that output by the Distribute Attributes plugin). Once this information has been obtained, the properties of the particular wall types, roof types, window types, etc, are read in from their respective dictionary of types to populate the CitySim XML file with the appropriate data for each building in the scene.

A GUI has also been developed into which additional information necessary for a CitySim execution is inputted by the user. This includes the path to the CitySim executable, the path to the climate file used by CitySim, the path to the output file where CitySim will dump the results files and information about the duration of the simulation period.

### 2.6 Attribute Update Plugin

The attribute update plugin allows the attributes associated with a QGIS vector layer, which has been pre-populated by the distribute attributes plugin, to be modified. The selection process by which buildings are chosen for attribute modification is greatly eased by existing functionality within the QGIS environment. A set of buildings maybe selected by:

- Clicking on each building in turn
- Drawing selection polygons around spatially localised groups of buildings
- Using the QGIS select by expression interface, whereby queries can be built to select set buildings by attribute values for example. The QGIS query builder could also be used.

Once selected the GUI developed with the plug allows the user to select the particular set of attributes they wish to change. By subsequently using Simulate CitySim plugin the modified scene can be simulated developing the next

snapshot in a scenario.

### 2.7 Results Analysis Plugin

A results analysis plugin has been created to interpret the results output by the simulation engine CitySim. In addition it enables the user to stitch together scenarios from consecutive changes to the scene (for example through the Attribute Update Plugin) and which are re-simulating with CitySim (via the Simulate CitySim Plugin). The plugin is able to make use of existing QGIS functionality for spatial analysis of the scene. It also has some basic standard plotting and statistical capabilities. Again a GUI has been developed in tandem with the plugin to facilitate its use.

## 3. Example Scenario

### 3.1 Scenario description

We perform a basic scenario to demonstrate the tool. The scenario will consist of a Manhattan Grid scene form of 200 buildings. Each building will have footprint dimensions 16m x 12m and be 4 stories high (each story being 3m tall). The scene will consist of two building typologies which we will refer to as "Victorian" and "Modern". We use this terminology because our typologies "Victorian" and "Modern" will have similar building thermal fabric properties to their namesakes, used in the Integrative Smart City Planning (InSmart) project [7]. Each Building will consist of 8 households with 2 residents per household.

To keep the scenarios simple we will alter only the building thermal fabric between the two typologies. All buildings will be equipped with a gas boiler which has a thermal efficiency of 90% and have a heating set point of 20°C. All other building variables will be set to same constant value for both typologies. The building types will be distributed throughout the scene with a uniform probability distribution ($P(X_i) = 0.5$). A summary of the probability distributions which vary between the two typologies is displayed in table 1. The glazing ratio probability density function also differs between the two typologies. The Victorian typology's glazing ratio is sampled from a uniform distribution between the values of 0.2 and 0.3. The Modern typologies glazing ratio is held fixed at a value of 0.2 (a dirac delta function distribution).

Table 1: The probability distributions associated with wall, roof and window type for the example scenario

|  |  | Probability | |
| --- | --- | --- | --- |
|  |  | Victorian | Modern |
| Wall Types | Double Brick | 0.9 | 0.05 |
|  | Cavity Clear | 0.05 | 0.35 |
|  | Cavity Insulated | 0.05 | 0.6 |
| Roof Types | Uninsulated | 0.6 | 0.1 |
|  | Insulated_100mm | 0.2 | 0.6 |
|  | Insulated_150mm | 0.2 | 0.3 |
| Window Types | Single Glazed | 0.8 | 0.2 |
|  | Double Glazed | 0.2 | 0.7 |
|  | Triple Glazed | 0 | 0.1 |

We will define a scenario as being made up of a list of strategies. A strategy is a planned change to the scene. A snapshot is taken of the scene before and after each strategy is applied. In the snapshot the annual energy demand and $CO_2$ production are calculated. The strategies employed as part of our current scenario will be:

- For all Victorian buildings which are uninsulated, apply 100mm of insulation
- Upgrade all single glazed windows to double glazed windows throughout the scene

### 3.2 Scenario results and basic tool demonstration

The results may be visualized in a variety of ways. Figure 3 displays a spatially resolved image of the buildings annual energy demands per m$^2$ of floor space at snapshot 0.



Legend

buildings
- 80.0-98.0kWh/m^2
- 98.0-116.0kWh/m^2
- 116.0-134.0kWh/m^2
- 134.0-152.0kWh/m^2
- 152.0-170.0kWh/m^2
- 170.0-188.0kWh/m^2
- 188.0-206.0kWh/m^2
- 206.0-224.0kWh/m^2
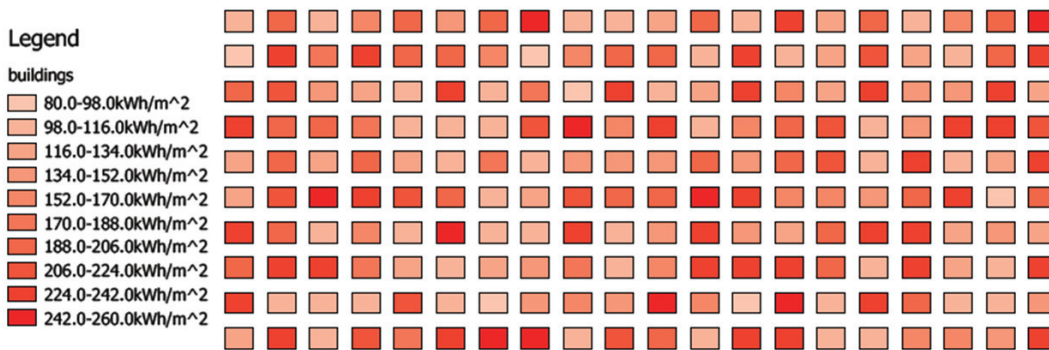- 224.0-242.0kWh/m^2
- 242.0-260.0kWh/m^2

Figure 3: Building footprints coloured according to their annual energy demand per unit area

It was mentioned in section 2 that one of the advantages of developing plugins to the QGIS environment is access to QGIS's extensive functionality. An example is displayed in figure 4 where the select by expression tool is used to develop a simple query to select Victorian buildings which are uninsulated.
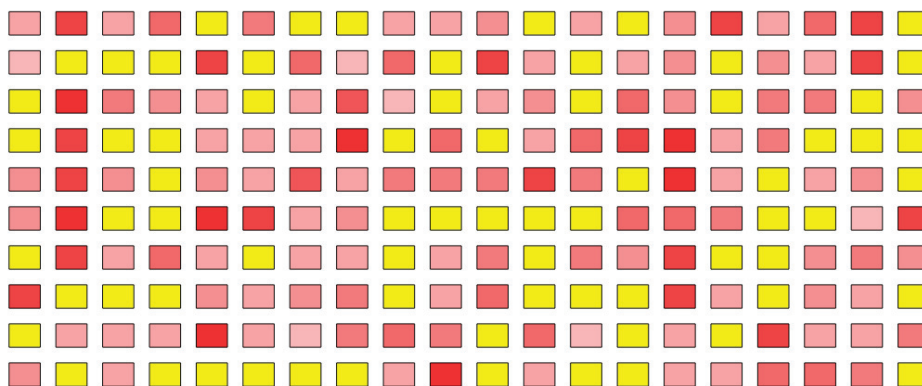


Figure 4: Selected features which satisfy the intersection of Victorian building type and uninsulated roof type

A useful feature within the Results Analysis plugin is the automatic generation of histograms of the energy demand per unit floor space distributions for each building type. These distributions are generated at each snap shot so that changes in these distributions can be visualised after the application

of each strategy (figure 5). Another automatic output at each snap shot is the total scene annual energy demand and the total scene annual $CO_2$ production (table 2).
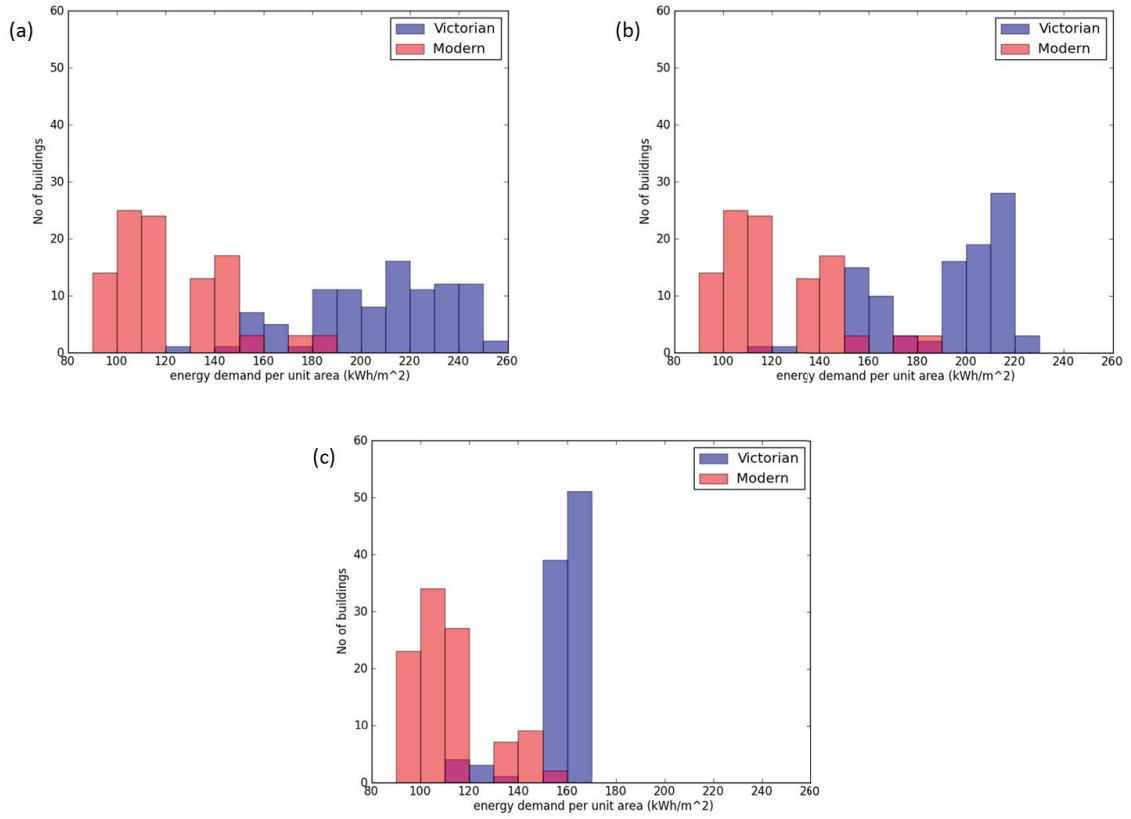


Figure 5: distributions of buildings by energy demand per unit area and by building type (a) snapshot 0 (b) snapshot 1 (c) snapshot 2

Table 2: The Annual Energy Demand and $CO_2$ Production for the whole scene

| Snapshot | Total Energy Demand (GWh) | Total $CO_2$ Production (tonnes) |
| --- | --- | --- |
| Snapshot 0 | 25.3 | 5196 |
| Snapshot 1 | 24.1 | 4953 |
| Snapshot 2 | 20.71 | 4255 |

*3.3 Brief Discussion*

The results of snapshot 0 are encouraging in that the energy ranges for both typologies approximately (we only such approximately to their typology values) agree with the results presented in the InSmart project [7].

The relatively large energy reduction in progressing from snapshot 1 to snapshot 2 is explained by a mixture of the large percentage of Victorian houses having single glazing and the relatively large glazing ratio attributed to this type.

It is interesting to note that the final reductions in annual energy demand and annual $CO_2$ production would have been accomplished by either permutation of these two strategies. However, the cumulative $CO_2$ emissions are order dependent and this has not been factored in thus far.

## 4. Future Work

There are a variety of avenues of possible development for the rapid urban de-carbonization scenario analysis tool. We touch on a few these here.

- Work is currently taking place within the LUCAS group to allow CitySim to read an input file with a CityGML compliant data structure CityGML [8]. These files are to be read in from a 3D City database. An obvious step is then to allow the plugins within the tool to populate the 3D City database, then to call an input file to be generated based on the populated database.
- It was mentioned in section 2 that an objective of the tool is to measure the energy and $CO_2$ consequences of indirect as well as direct emissions. This requires a representation of time within the scenarios, something which has already be pointed out as important in section 3. Work to incorporate indirect emissions is to begin shortly.
- Plans are also being made to incorporate the approximate financial costs of renovations within the tool. This will allow the user to be constrained by budget as well as by $CO_2$ emission targets
- In order to have more control of the spatial distribution of attributes, it is planned to incorporate an addition QGIS vector layer defining background zones. Probability distributions and density functions may then vary spatially between zones.
- The statistical suite within the Results Analysis plugin is presently limited. This is to be greatly expanded in the near future
- Finally is seems a logical step to now test and apply the tool over a range of hypothetical and real city test cases

## 5. Conclusion

A rapid urban de-carbonization scenario analysis tool is in development which can be used to develop and analyze scenarios involving large scale spatially resolved building scenes for energy simulation within the CitySim Simulation Engine. The tool has been designed as a series of plugins to the QGIS application so that existing QGIS functionality and software libraries can be utilized. A total of six plugins have been developed so far and are at various stages of development (section 2). All plugins are at a suitably advanced stage of development such that tip to tail scenarios can be generated, as was demonstrated in section 3. A proof of concept has taken place whereby many of the objectives of the tool (described in section 2.1) have been met.

Section 4 touched upon some of the expected near term future development of the tool.

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