MSc thesis in Geomatics

Building massing generation using ***GAN*** trained on Dutch 3D city models

Ondřej Veselý

2022

Context

The state of computational tools applied to architectural and urban design practice.

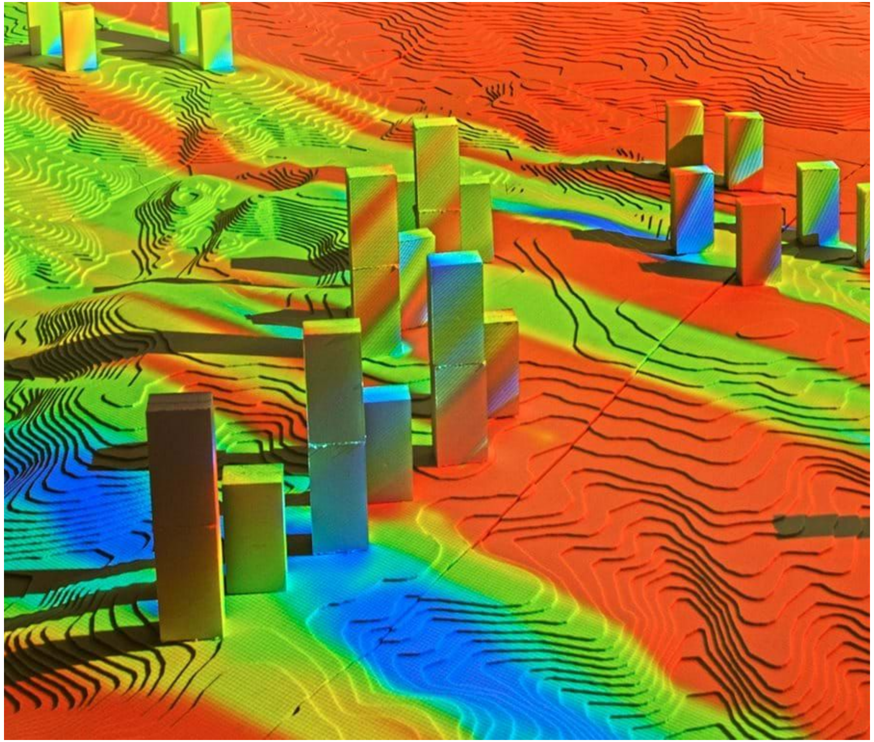
Computational design

Industry increasingly dependent on use of computers to model and evaluate the built environment

→ it is possible to **evaluate** more design options in **earlier** design phases

→ it is beneficial to **explore** large and diverse set of **options** as early in the process as possible

“computer scientists work along with designers [...] to offer bespoke digital solutions for architecture and the construction industry” (Carta, 2021)



Collaborative Design Tool (Foster and Partners, 2021)
Available at https://www.fosterandpartners.com/expertise/applied-research-development/

Generative design

Research on generative design methods for creating building layout variants, often using rule based algorithms*

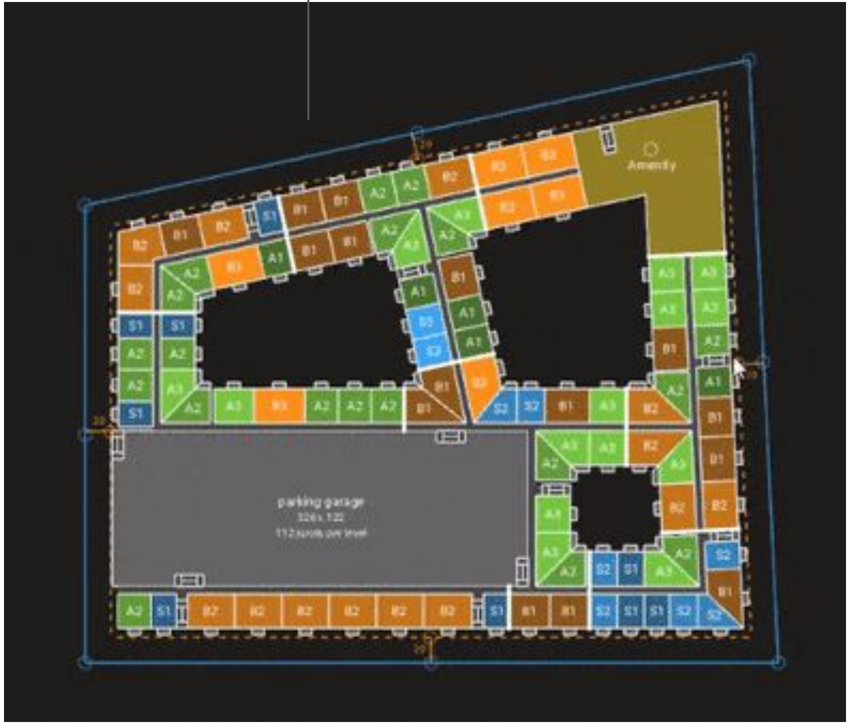
Targeting repetition and standardization:

- residential, office, hospital
- modular construction systems

*see *TestFit, Kreo Modular, SpaceMaker*

The massing design variability is limited, and are not informed by the site context.

Massing conforms only to the plot shape, using rules defined by the user

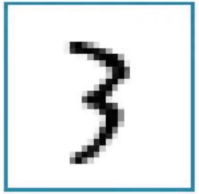


Testfit.io
Available at https://testfit.io/

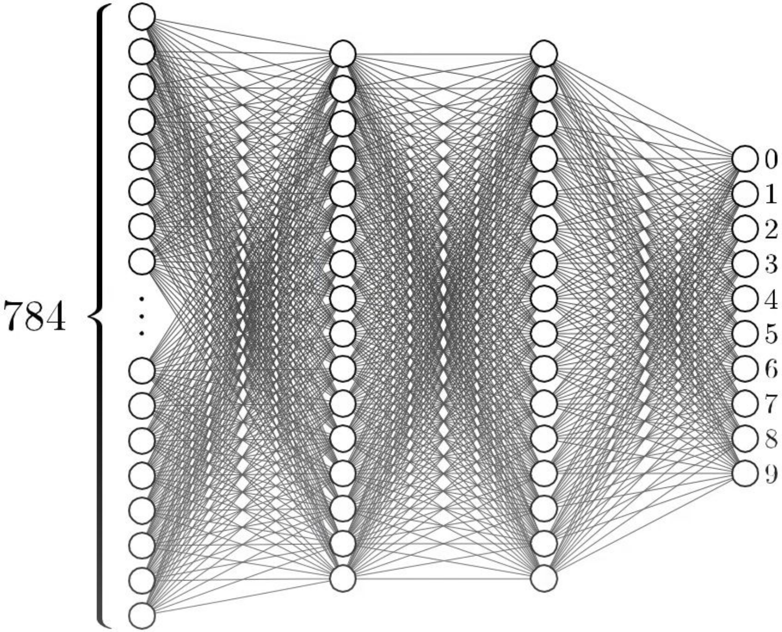
Theoretical background

How can a computer help us generate diverse set of suitable massing options, which are informed by the site context?

Neural networks



28x28px image
(784 pixels)

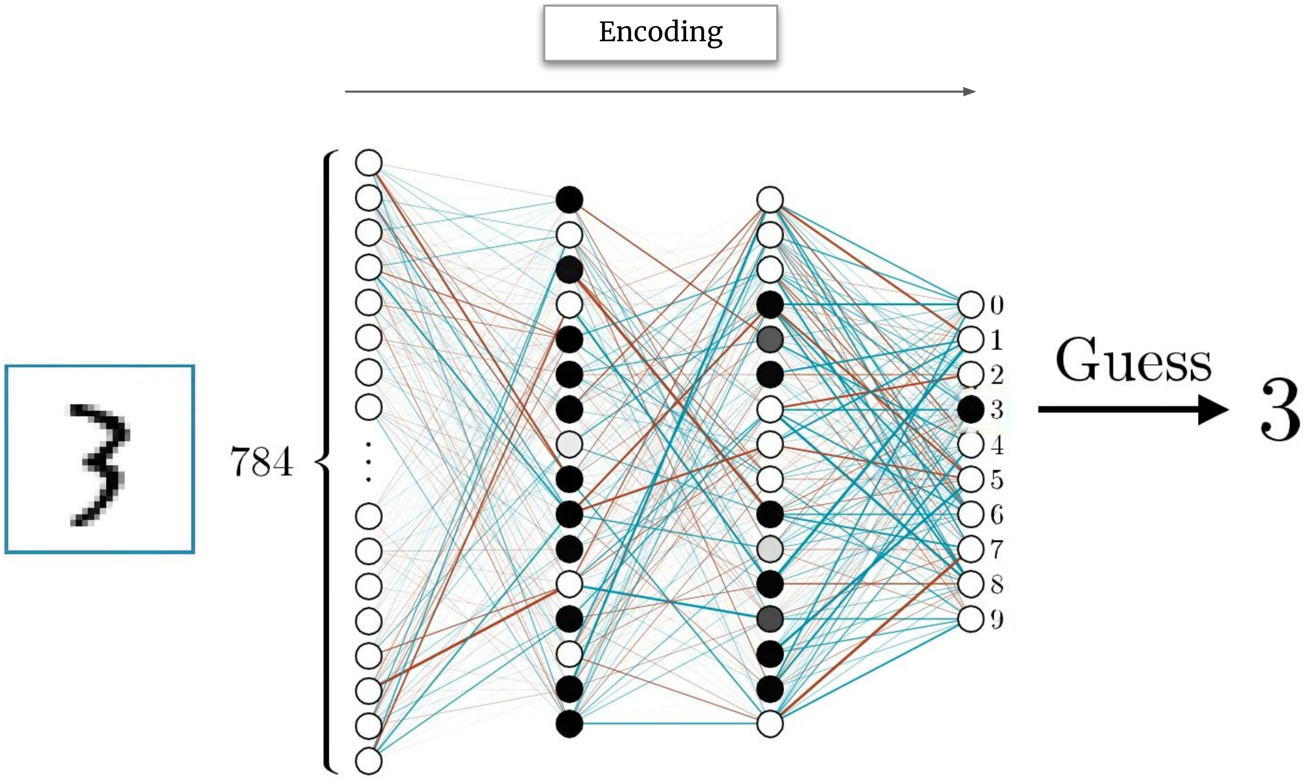


?

Which one of
10 digits?

Images adapted from 3blue1brown video - Gradient descent, how neural networks learn
Available at https://www.youtube.com/watch?v=IHZwWFHWa-w

Neural networks



Images adapted from 3blue1brown video - Gradient descent, how neural networks learn
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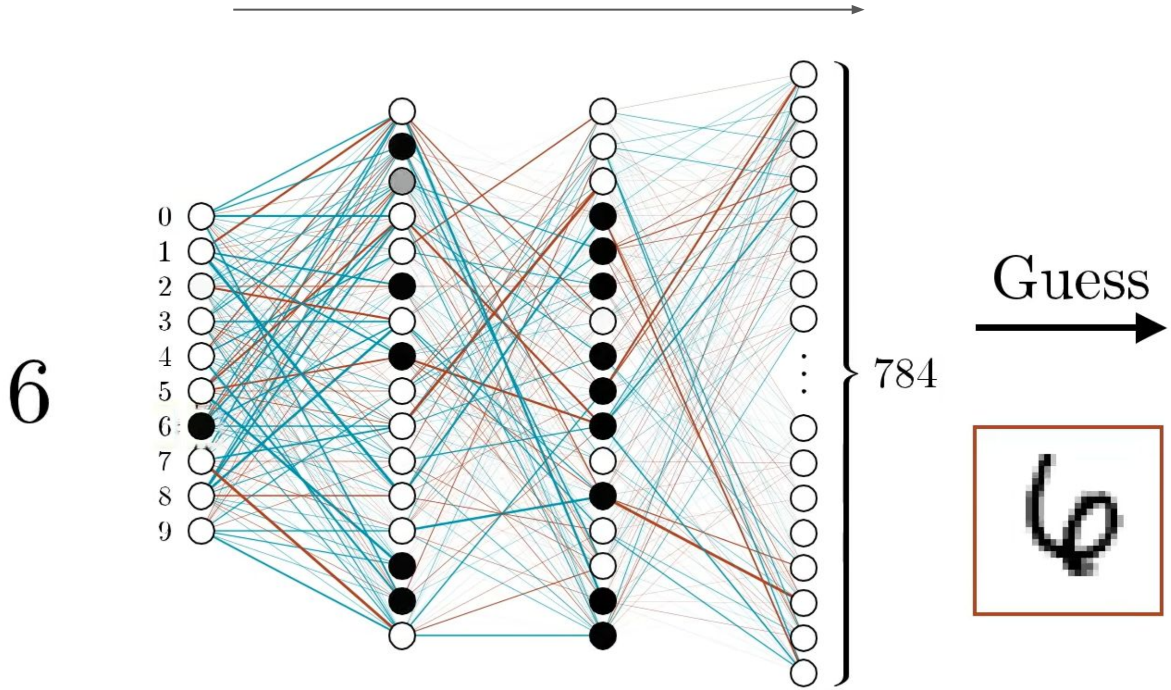
Neural networks

Decoding*



*This slide is a huge oversimplification

Images adapted from 3blue1brown video - Gradient descent, how neural networks learn
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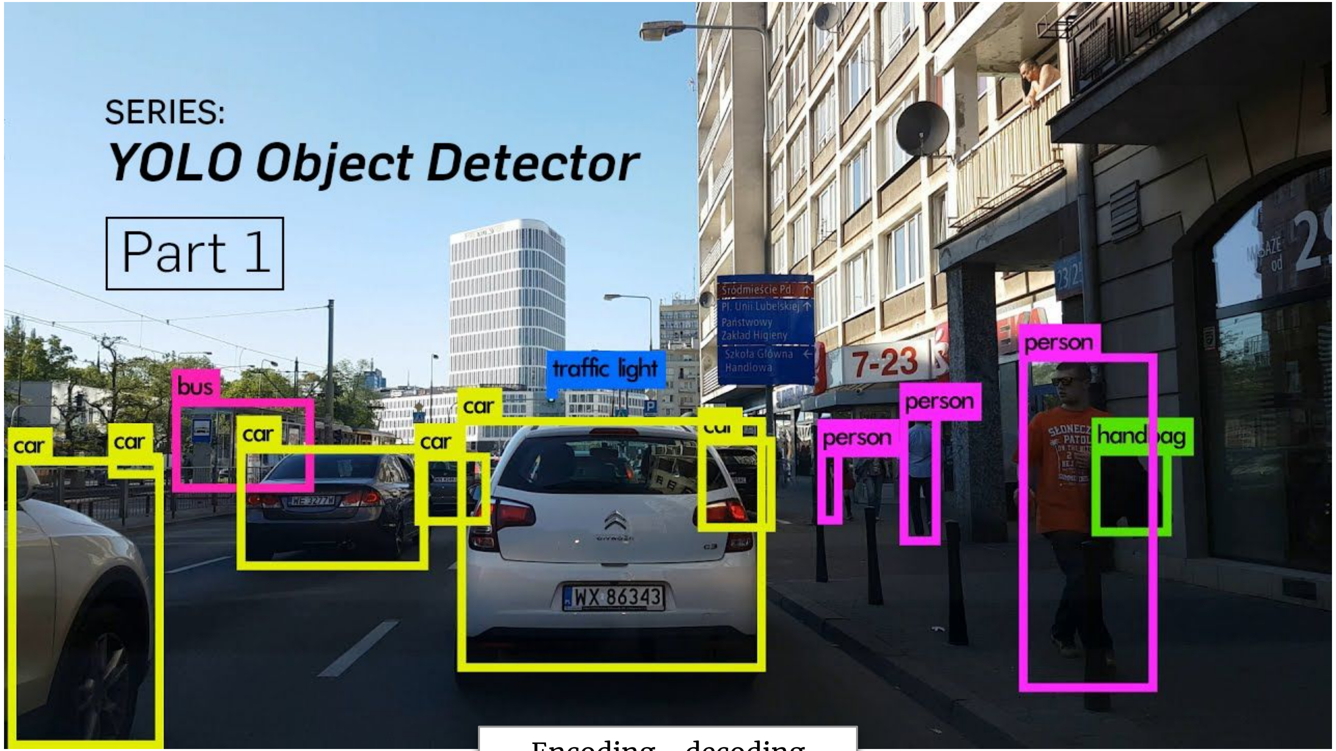
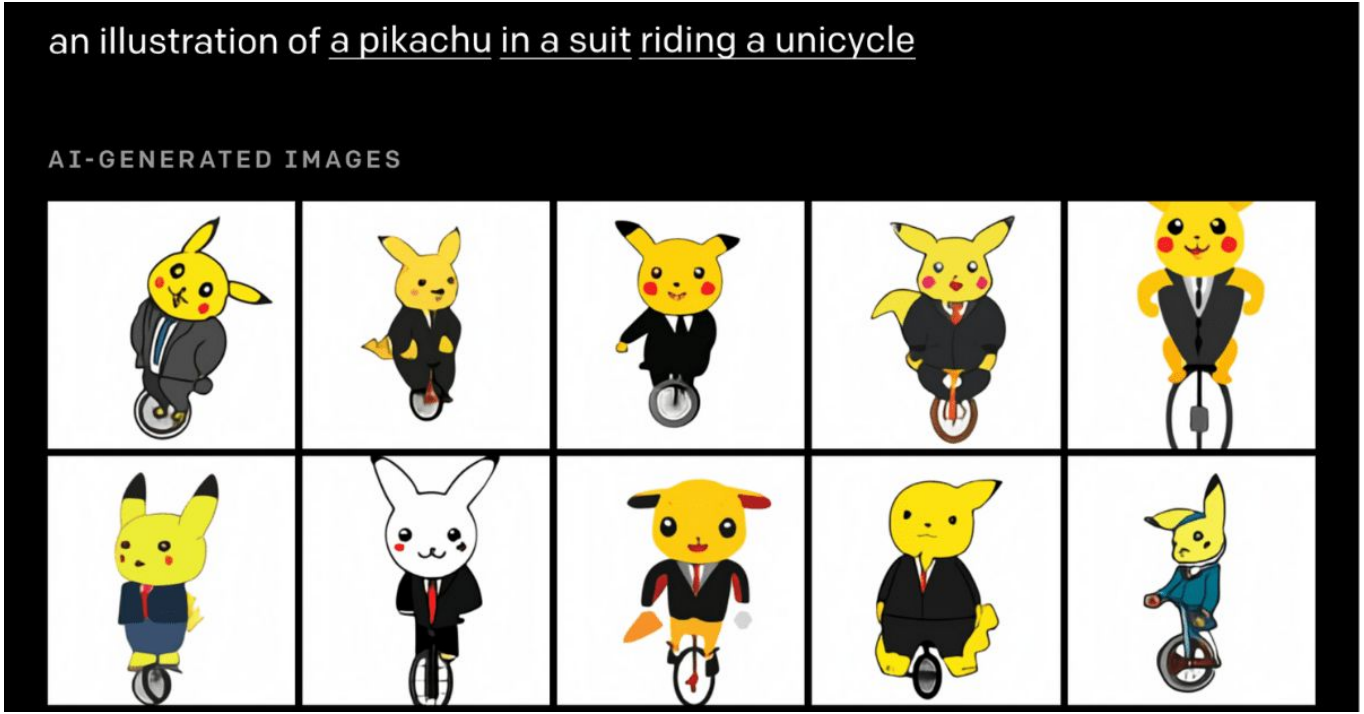
Neural networks



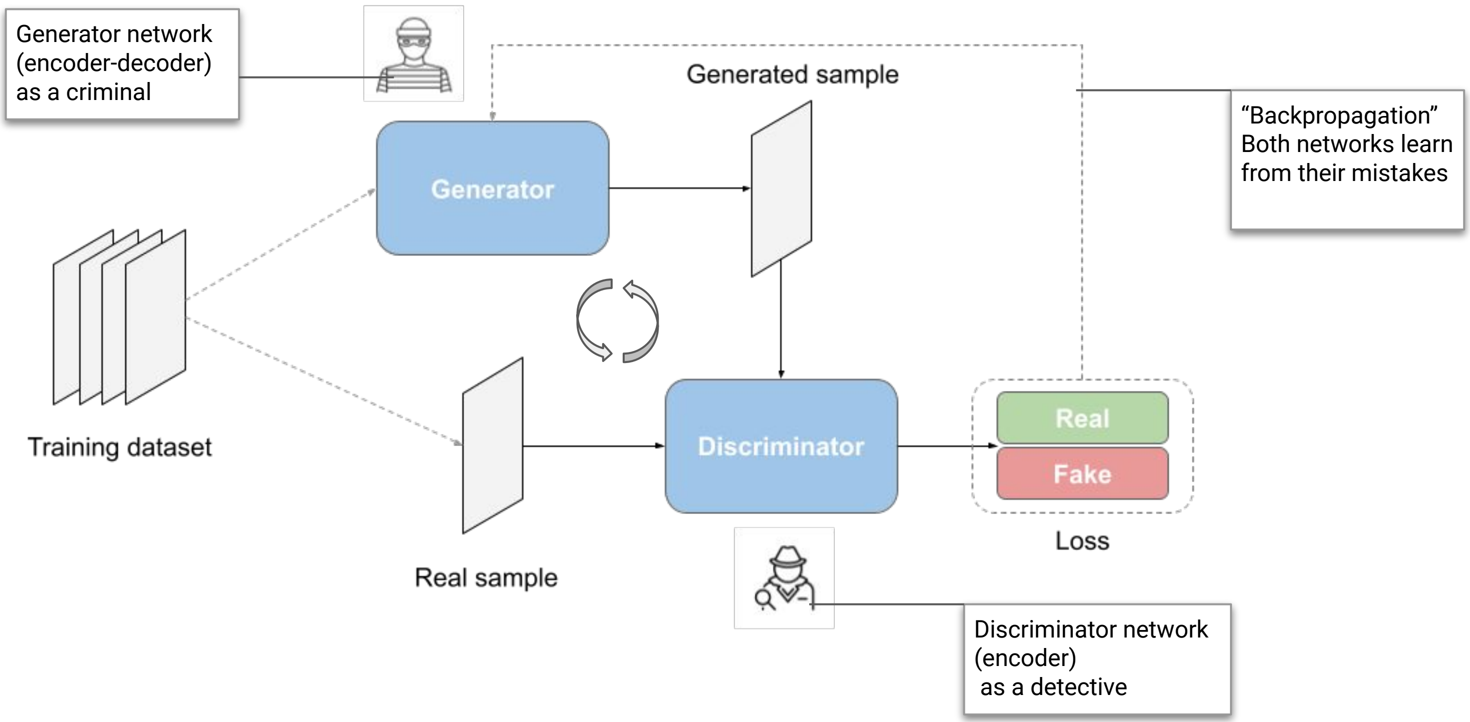
Encoding – decoding
image to object labels

Neural networks

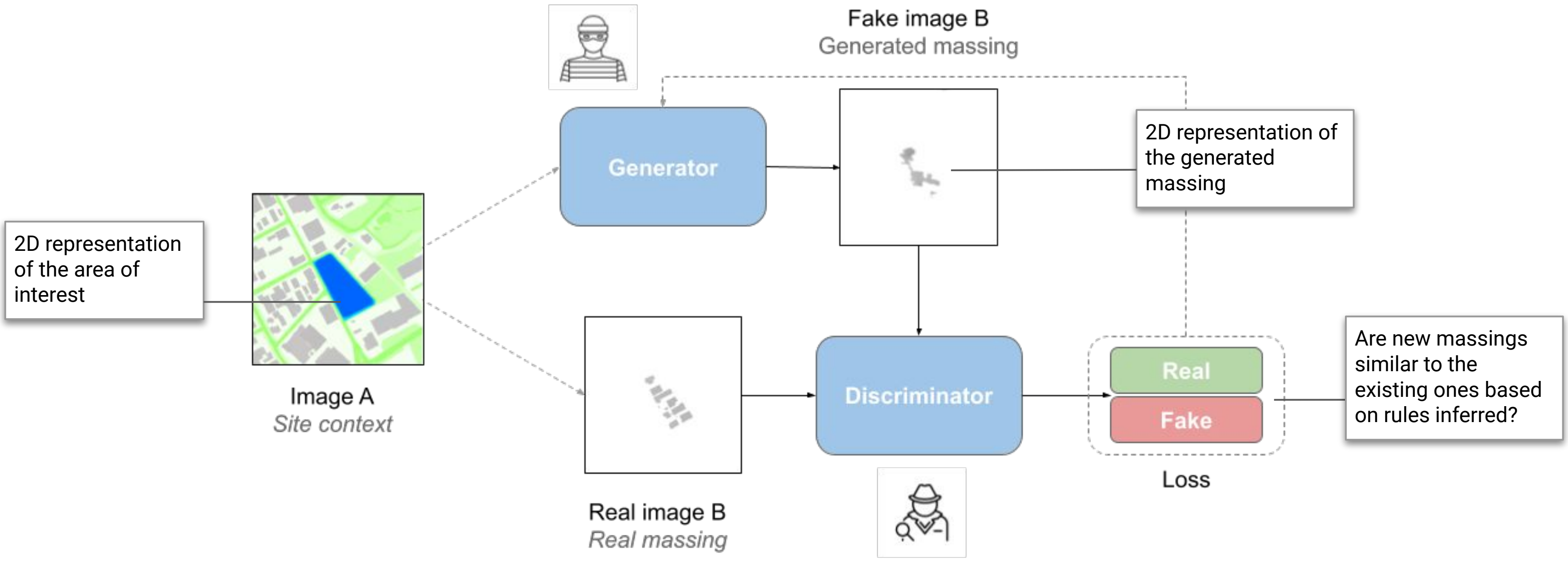


Encoding-decoding text to generated images

GAN - Generative adversarial network



Proposed GAN model



Related work

What are the relevant precedents?

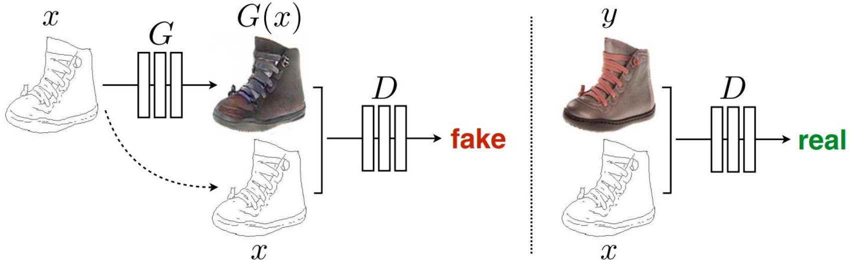
Pix2Pix GAN

[Isola *et al.*, 2017]

Picture to picture translating generative adversarial network

Trains on **paired images**
→ to map image A to image B

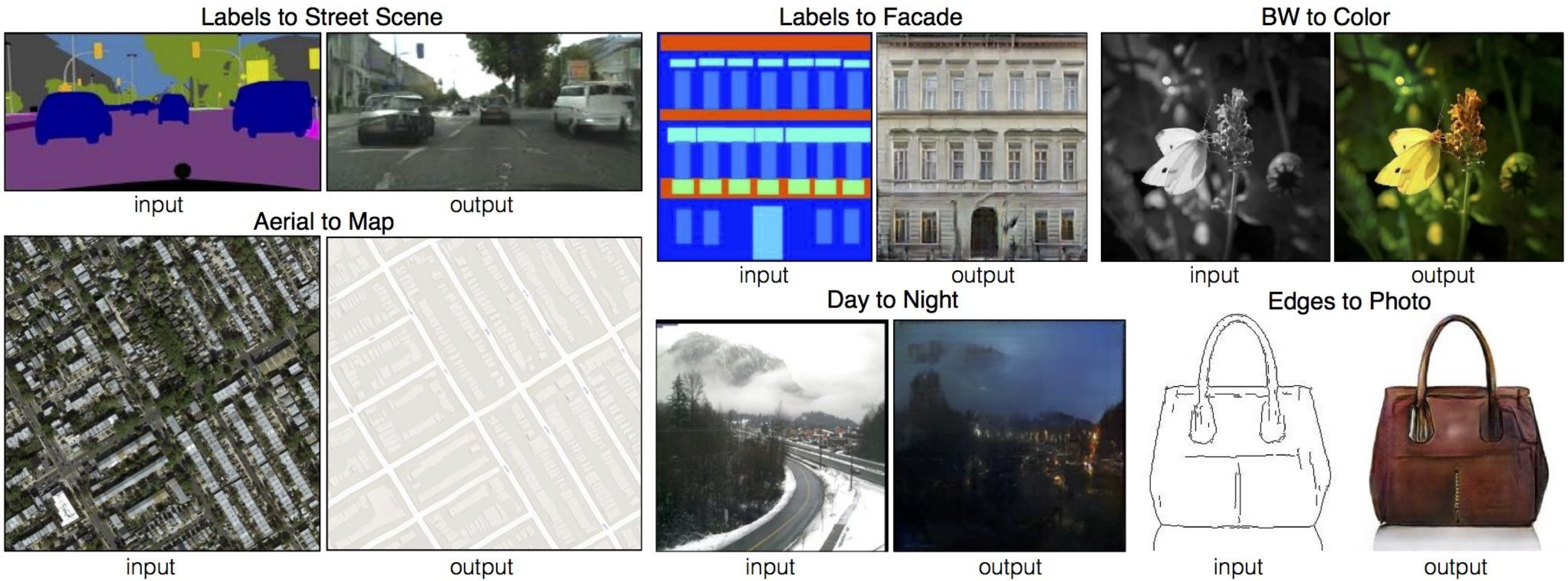
Powerful model with relative **ease of use**
Popular with artist and designers



Training a conditional GAN to map edges→photo
Isola, P., Zhu, J.-Y., Zhou, T., and Efros, A. A. (2017). Image-to-Image Translation with Conditional Adversarial Networks.

Example of the results
Isola, P., Zhu, J.-Y., Zhou, T., and Efros, A. A. (2017). Image-to-Image Translation with Conditional Adversarial Networks.

Pix2Pix GAN



Example of the results
Isola, P., Zhu, J.-Y., Zhou, T., and Efros, A. A. (2017). Image-to-Image Translation with Conditional Adversarial Networks.

GAN in architecture

[Chaillou, 2019]

ArchiGAN: a Generative Stack for Apartment Building Design

Pix2pix GAN applied to the design of the residential units

1. footprint
2. functional zoning
3. furniture placement

ArchiGAN: a Generative Stack for Apartment Building Design (Chaillou, 2019)

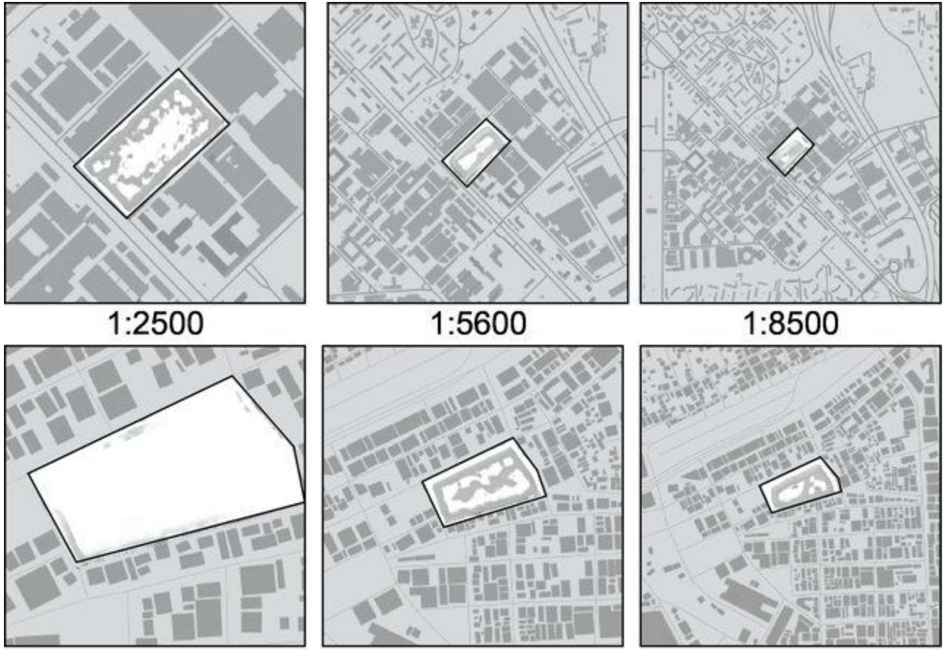
GAN in urban design

[Fedorova, 2021]

GANs for Urban Design

Comparing street blocks from different cities and results of training at different scales

Trained on **footprints** and **street network** center lines



Generative Adversarial Networks for Urban Design (Fedorova, 2021)

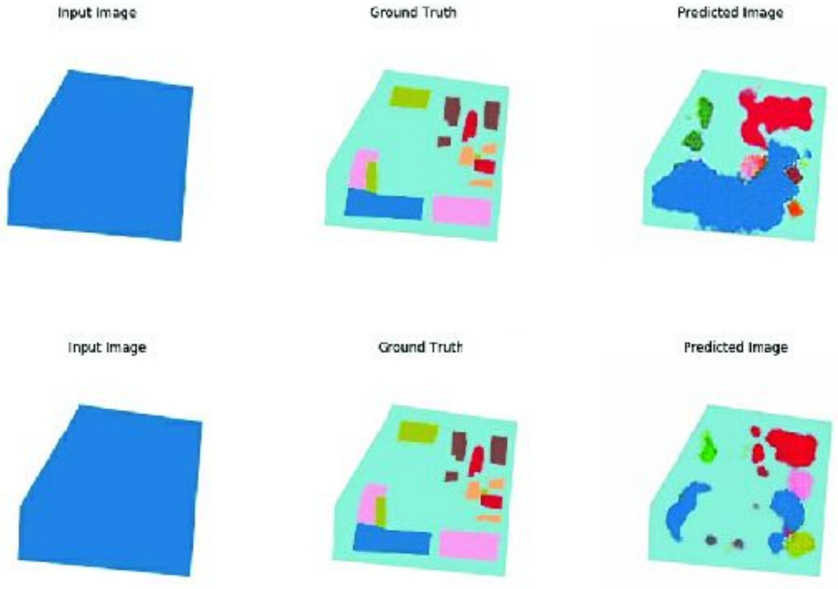
GAN for site layout

[Tian, 2021

Suggestive Site Planning with Conditional GAN and Urban GIS Data

Generation of **building group** layouts including the assigned **building use**

Based only on the **site shape**



Suggestive Site Planning with Conditional GAN and Urban GIS Data
(Tian, 2021)

Conclusions

1. Relative lack of site context information and low **level of detail** of the input data.

2. Lack of rigorous **evaluation** of the results beyond visual comparison of images.

3. Lack of methods to transform the output image values into **3D geometry**.

Goals and objectives

What are the goals and scope of the proposed research?

<u>Scope and goals</u>

1. Use **<u>Pix2Pix GAN</u>** as a well explored method for design generation.

2. Explore **<u>3D BAG</u>** dataset for as source of high **<u>level of detail</u>** building geometry.

3. Explore methods to transform the output image values into **<u>3D geometry</u>** and methods to **<u>evaluate</u>** the quality of results.

Research questions

To what extent can one **assist** the process of **building massing design** by utilizing **GAN model** trained on existing building forms?

At what **scales** is the method applicable (building, small block, larger area)?

Can the model be **steered** towards certain typological **traits**?

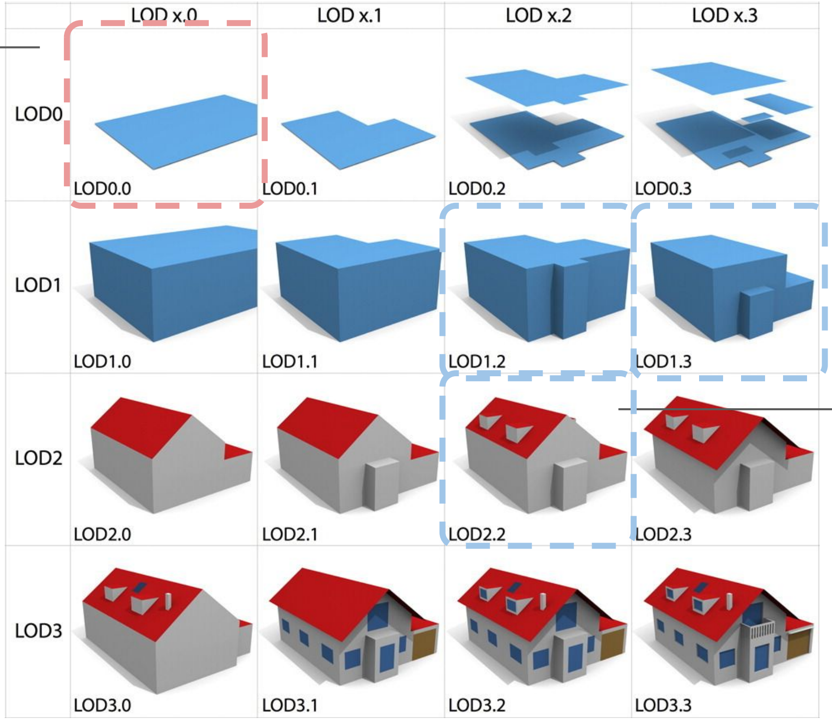
How important is the **level of detail** of the massing geometry and the included context?

Methodology

What methods and frameworks did I choose to implement to investigate the research questions?

Level of detail

Existing works using only footprint shapes



My targets retrieved from 3D BAG

improved LOD specification for 3D building models (Biljecki et al., 2016)

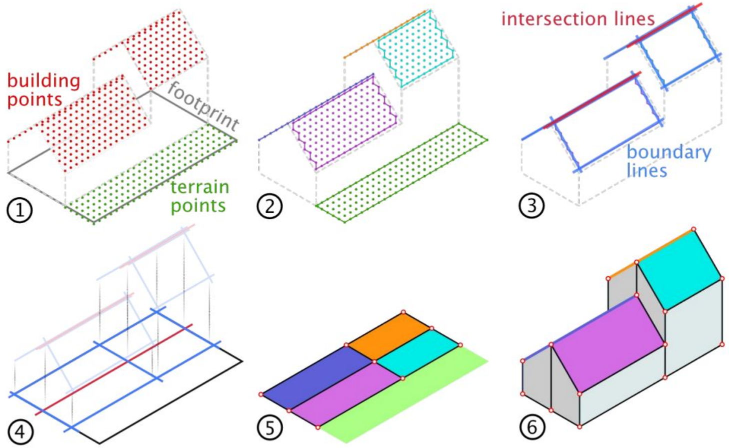
3D BAG

3D BAG is a dataset with geometry of the of ~9 million building objects in the Netherlands

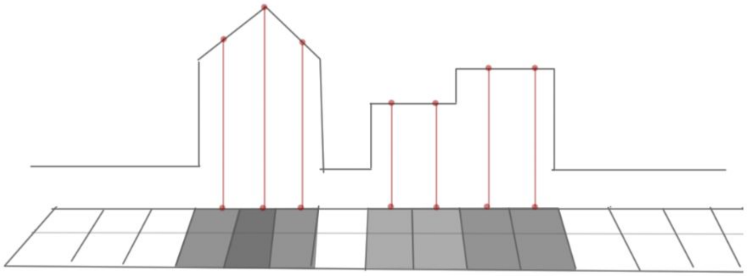
Based on AHN3 (LiDAR point-cloud of the Netherlands) and BAG (register of all buildings and addresses

Developed by 3D geoinformation @ TU Delft

Roofs as planar partition → no overhangs!

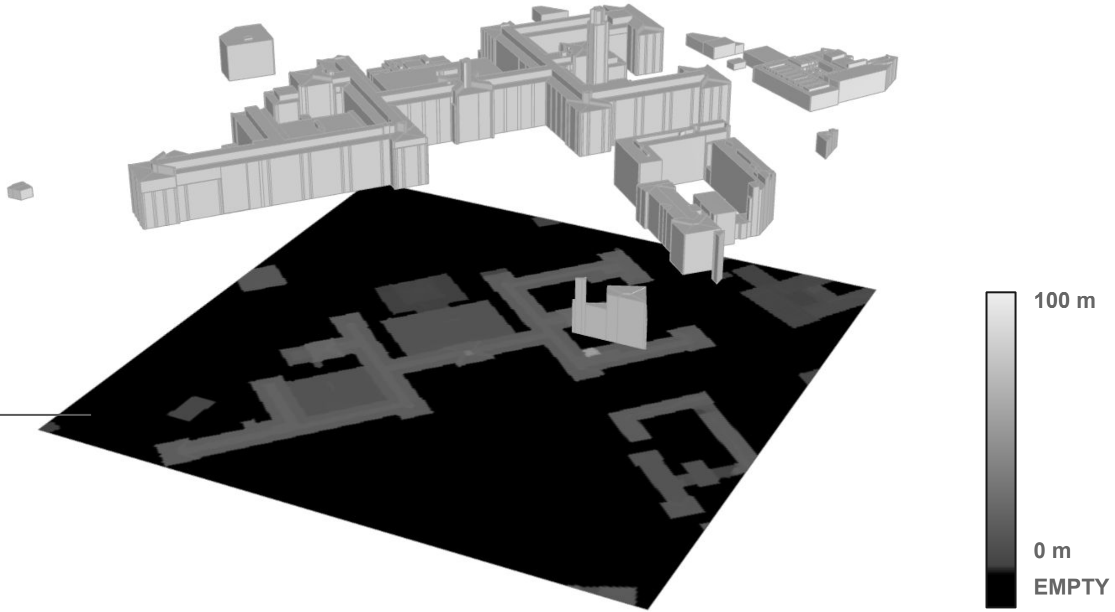


Process of building geometry reconstruction used by 3D BAG (Peters R., 2020)



Mapping between height-map values and 2.5D surface model

Heightmaps



Geometry mapped to its height-map representation
→
Image based representation of three-dimensional model the GAN can consume

3D BAG geometry mapped to its height map representation

Site context

Site context data acquired from additional Dutch open data sources -

TOP10NL

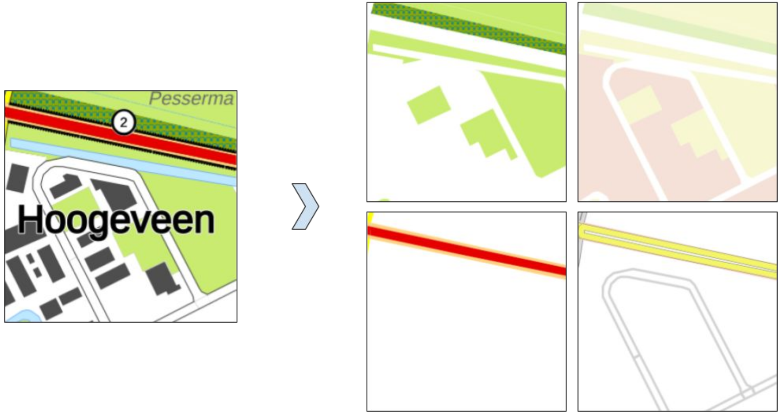
- Natural features
- Land cover
- Road surfaces
- Road hierarchy

BRK

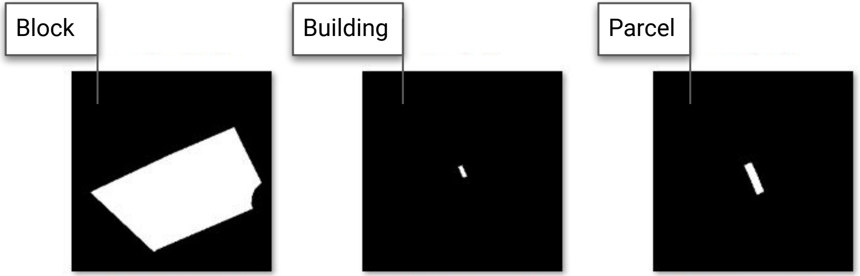
- *Parcel / plot extents*

NWB

- *Street block extents*

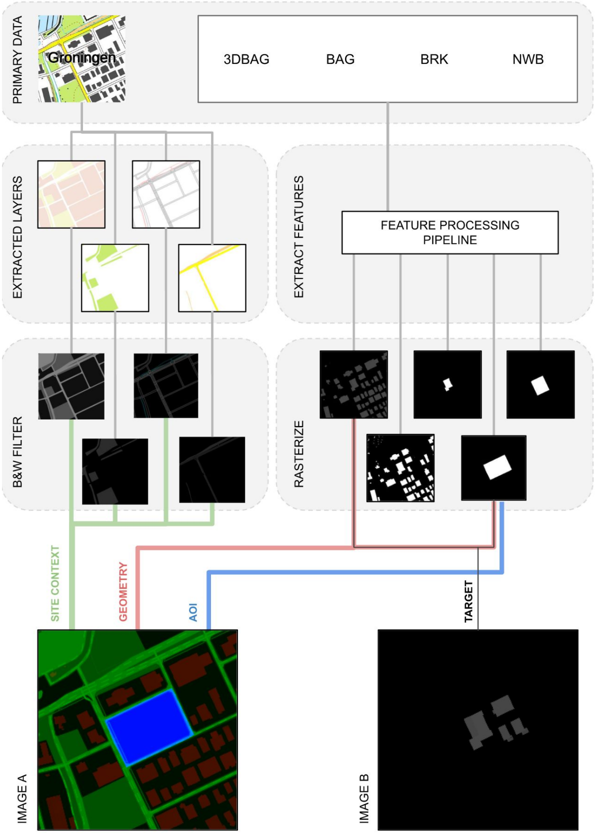


Different site context layers extracted from TOP10NL national topography



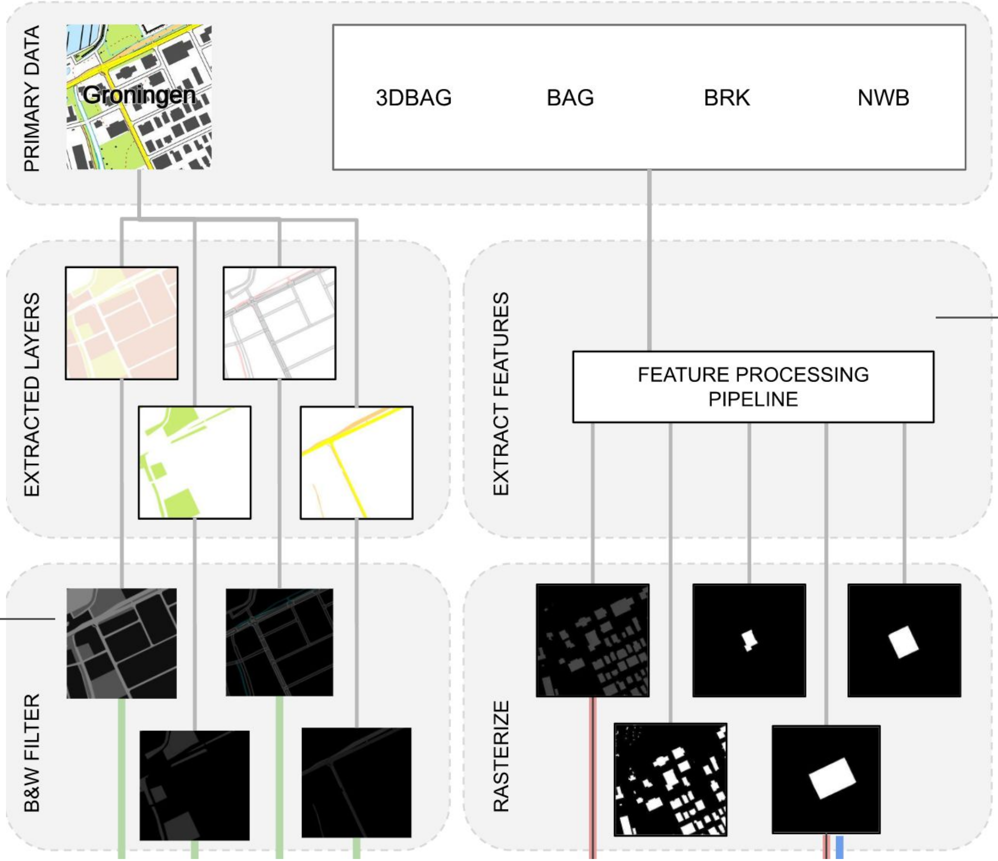
Block, single building and a parcel target masks for an area

Image pair generation



Overview of the data collection pipeline

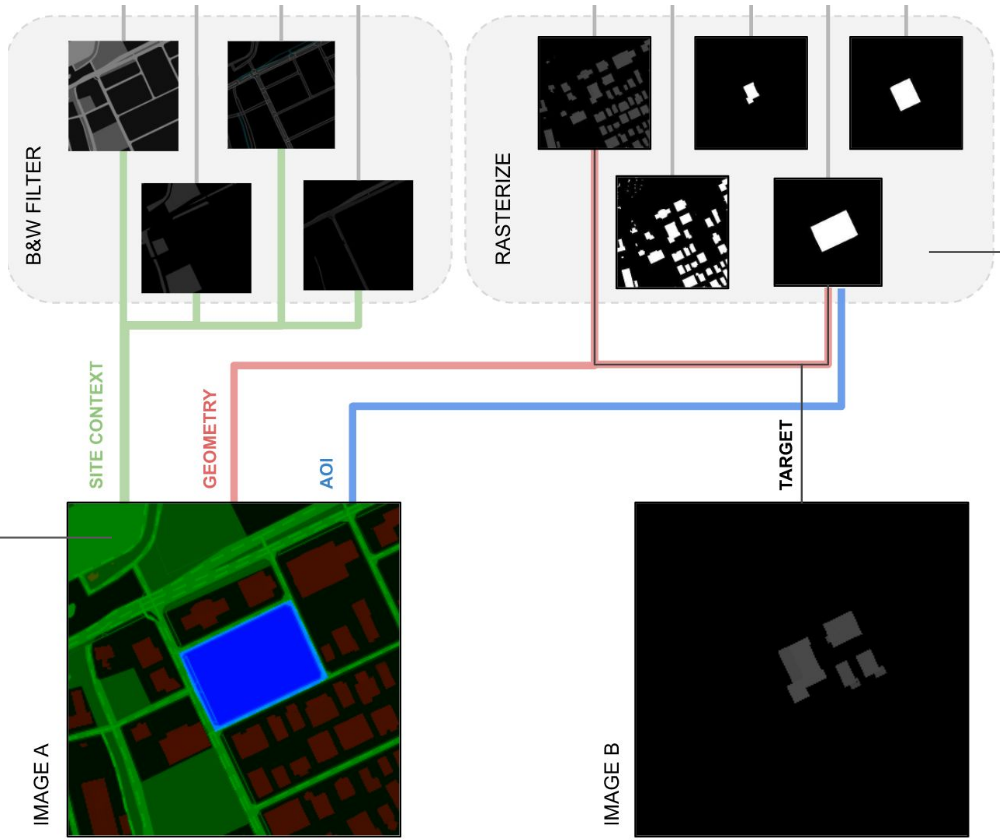
Image pair generation



Additional semantic and quantitative data stored for further filtering purposes.

Converting to grayscale representation for more modular data layers

Image pair generation



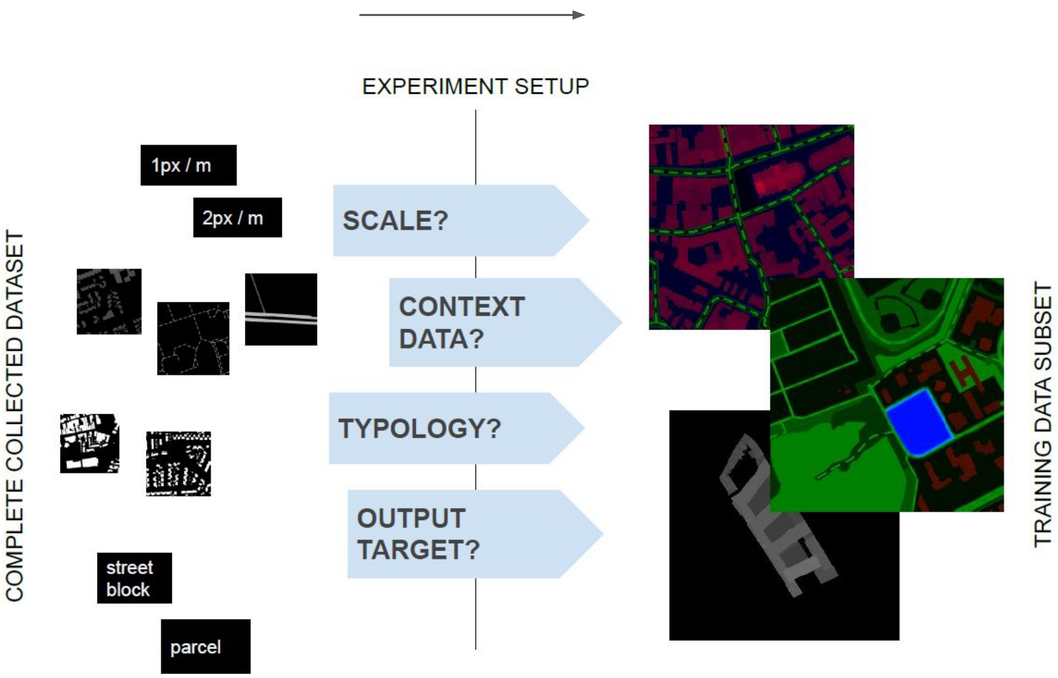
Features in the training dataset filtered based on their properties.

Create datasets targeting specific situations.

Choose a specific combination of features based on the goals.

Different layers encoded in RGB channels

Experiments



Residential street block generator

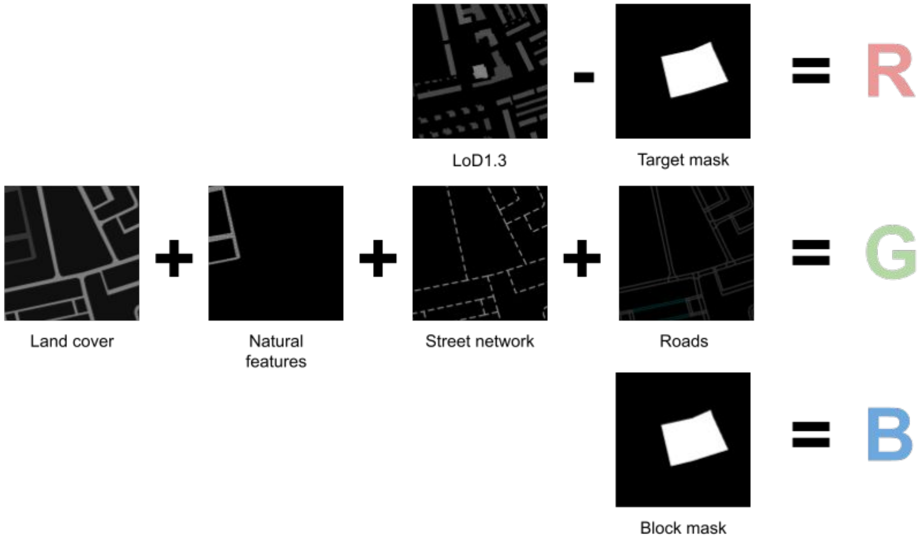
Experiment #2

Is the model capable of generating street block layouts?

Study focused on residential typology

Trained on 1,000 training data samples

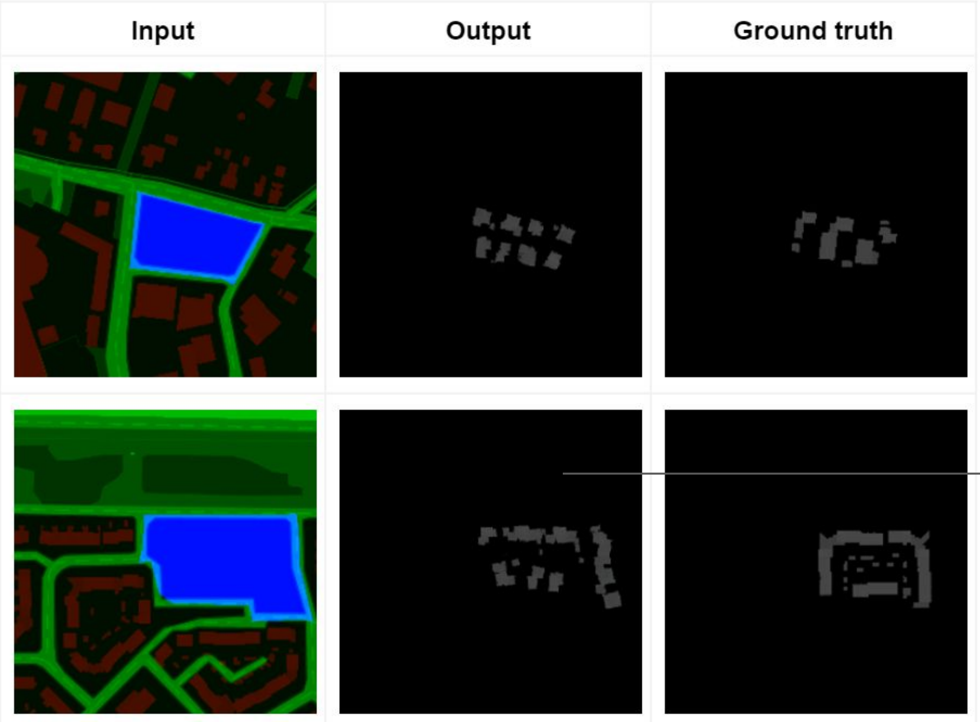
1. Blocks with only **residential use**
2. Built between **1990 -- 2010**
3. Floor space between **200 -- 1000m²**



Included spatial data layers

Residential street block generator

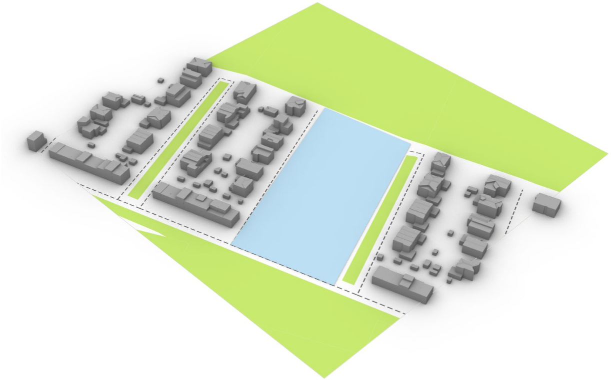
Experiment #2



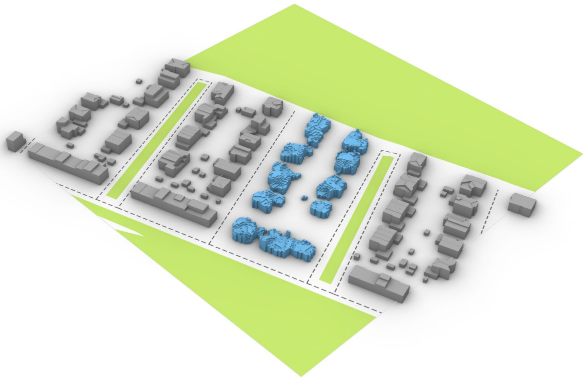
Tendency to generate free standing volumes

Residential street block generator

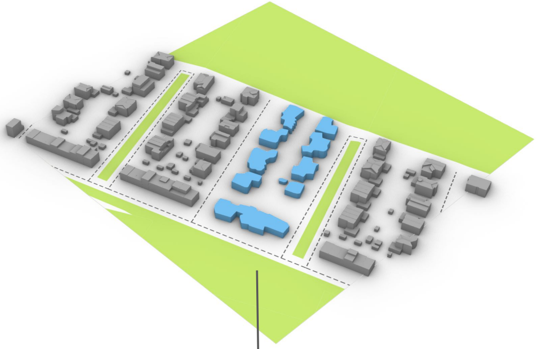
Area of interest



Voxelized output



Vectorized output



Recreates the block pattern present in the surrounding area

Bloemkoolwijk street block generator

Experiment 3.

Is the model capable of learning specific spatial typology?

Study on so-called *Bloemkoolwijken*

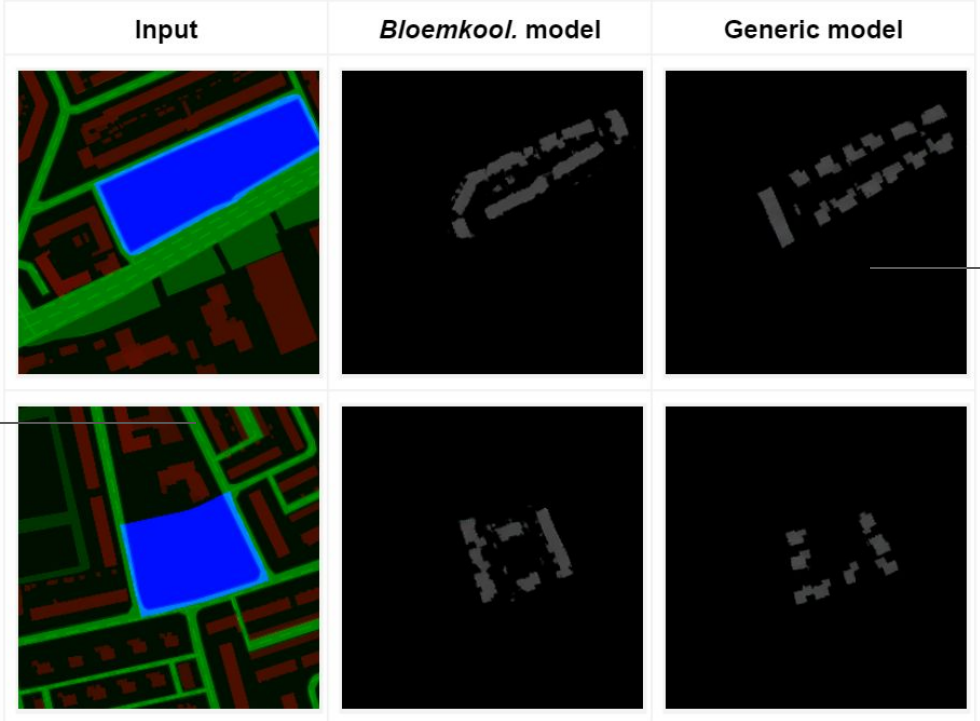
Bloemkoolwijken (cauliflower neighbourhoods) are specific **Dutch urban planning** phenomena, built between **1970 -- 1990.**

Focused on three specific neighbourhoods as the source of data:

- **Kronenburg** in Arnhem
- **Peelo** in Assen
- **Holy-Noord** in Vlaardingen

Blank, R., 2022. MaHKU - The Bloemkoolwijk - Networks and Cinematic Urbanism. [online] Mahku.nl. Available at: <https://www.mahku.nl/ma_studies/public_space_design_alumni_1288.html> [Accessed 18 May 2022].

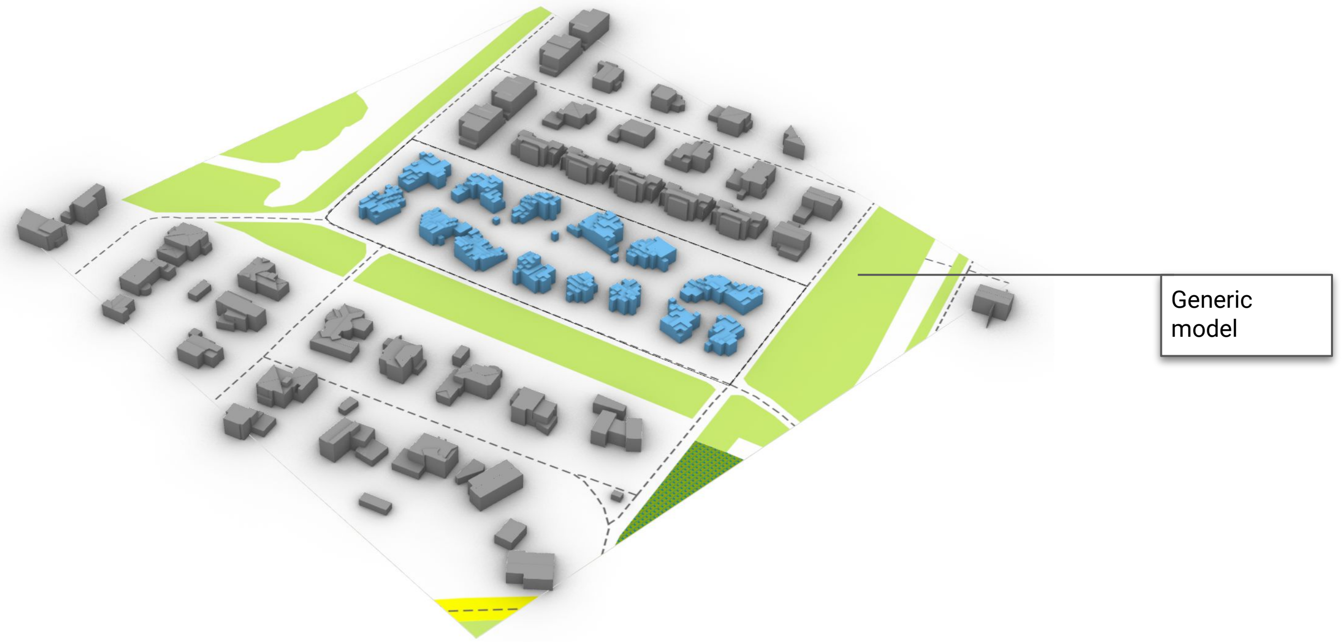
Bloemkoolwijk street block generator



Bloemkoolwijk model generates more linear street fronts compared to the generic model from experiment 2.

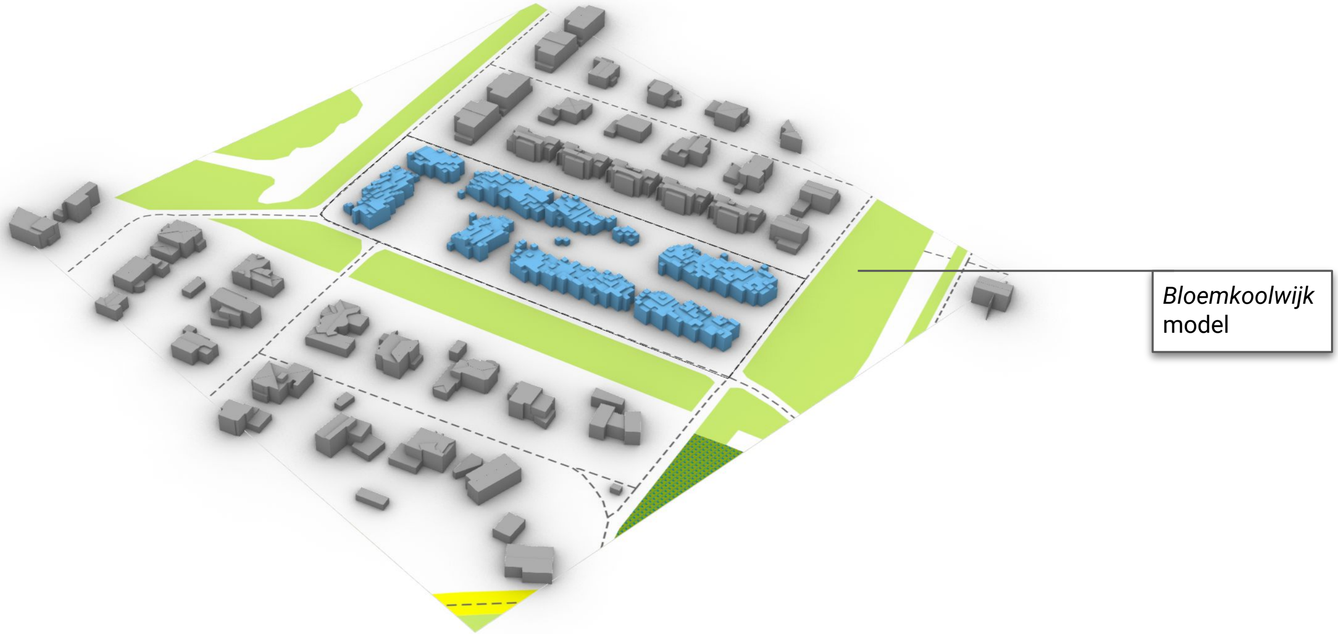
Bloemkoolwijk model and generic model have been applied to validation sites from both bloemkoolwijk and generic dataset.

Bloemkoolwijk street block generator



Results from Residential street block generator

Bloemkoolwijk street block generator



Results from Bloemkoolwijk street block generator

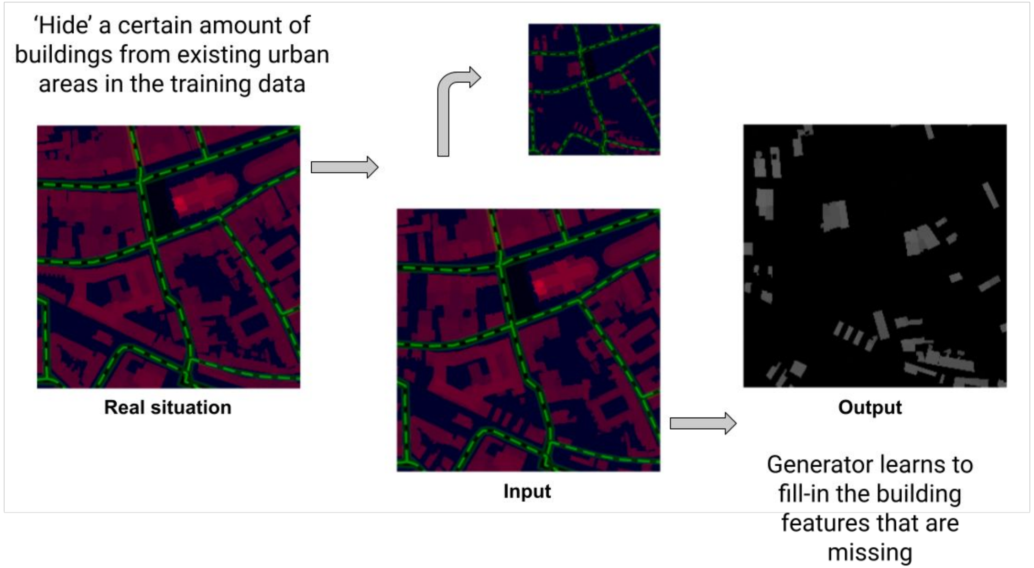
Urban fabric densification

Is the model able to identify potential locations for urban infill?

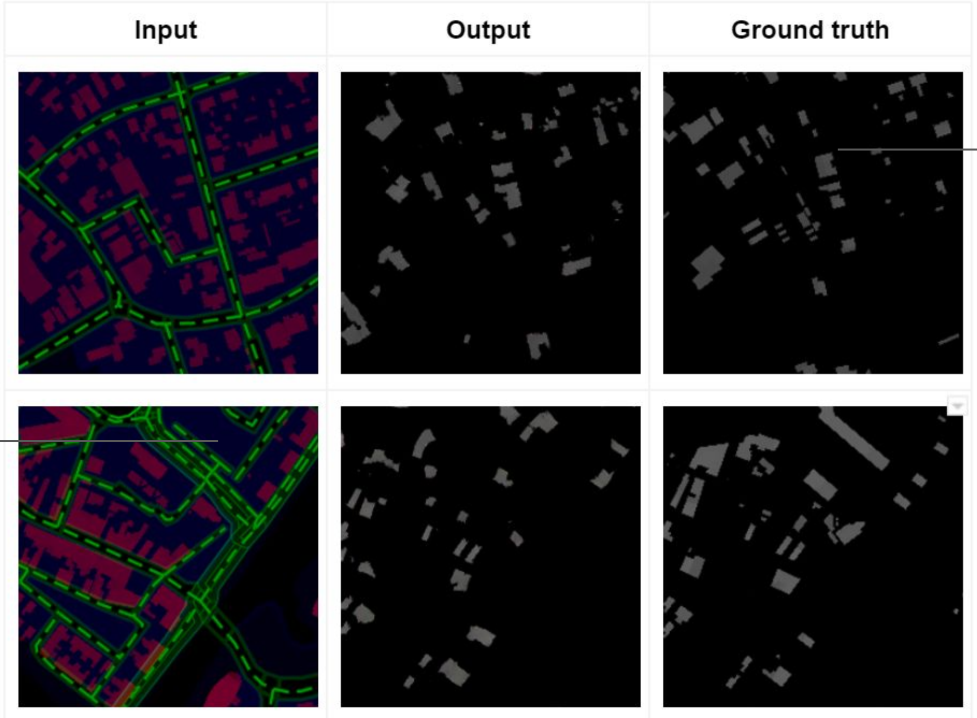
Trained on **semi-synthetic data**.
Dense urban areas with a percentage of building removed.

The goal for the model is to **identify the gaps**.

Therefore it learns to fill in gaps in **urban fabric** once applied to real data.



Urban fabric densification



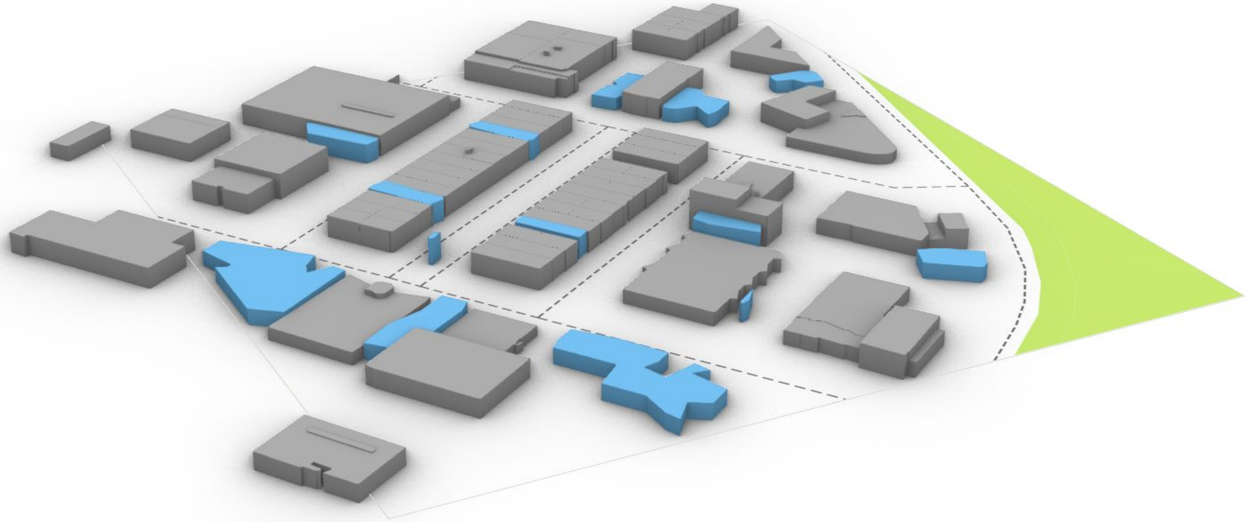
The model is able to fill-in the synthetic gaps

In areas without context information, it struggles

Urban fabric densification

Results from Urban fabric densification model

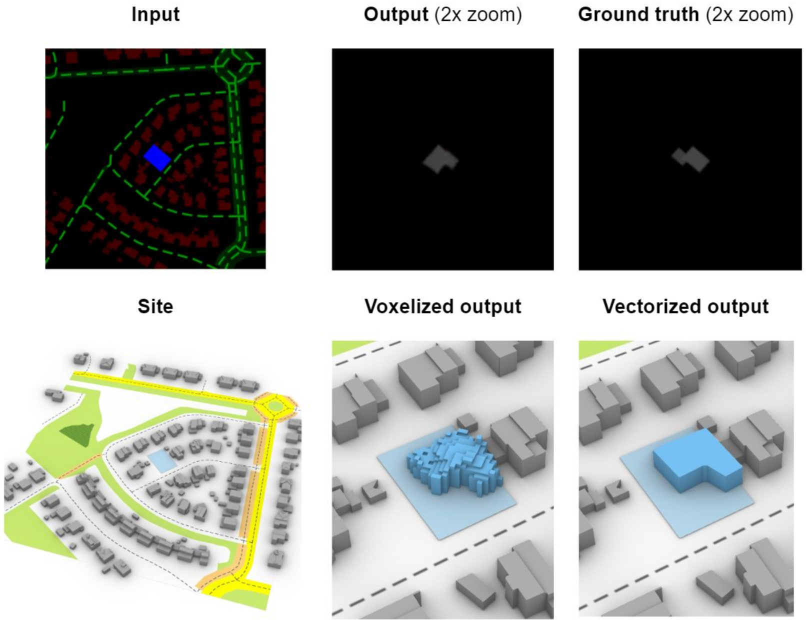
Urban fabric densification



Results from Urban fabric densification model

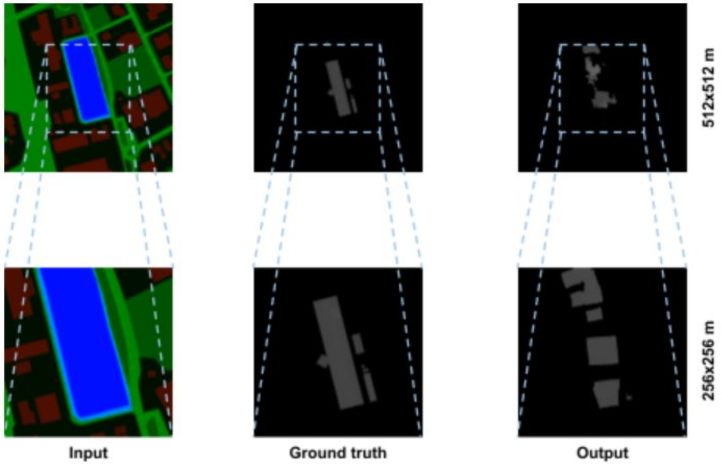
Other experiments

Single residential building generator

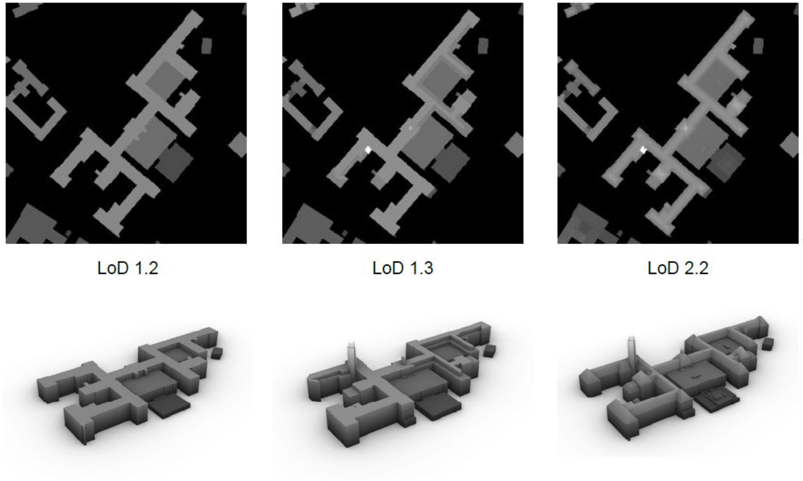


Other experiments

Study on scale



Study on level of detail

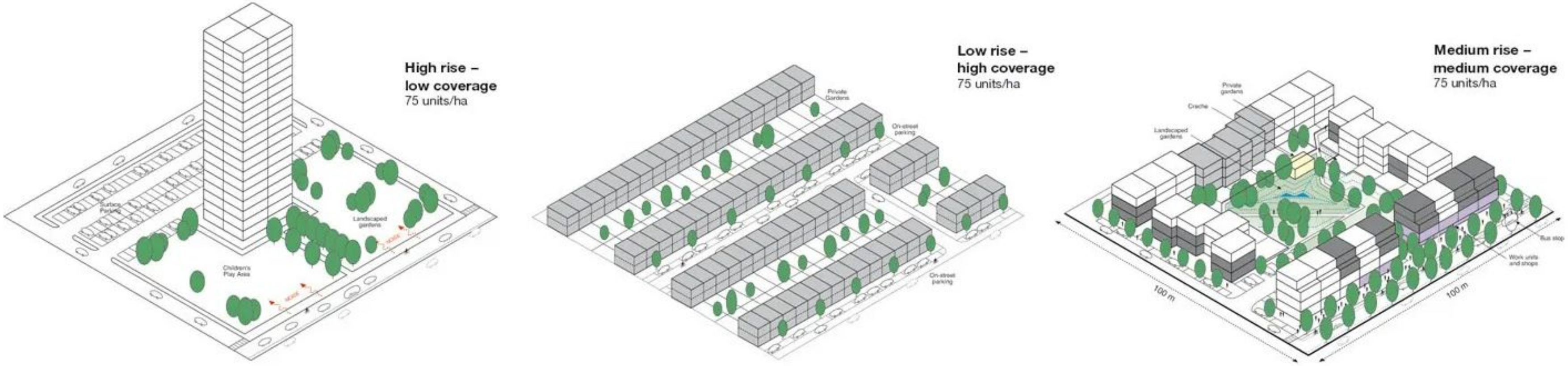


Evaluation

How to evaluate the ability of the model to replicate typological traits using quantitative analysis?

Quantitative typology

75 identical housing using placed on 100x100 plot



How to quantify the difference?

Urban morphological types for identical unit count (image from Richard Rogers [1999] 'Towards an Urban Renaissance')

Spacematrix

Floor Space Ratio

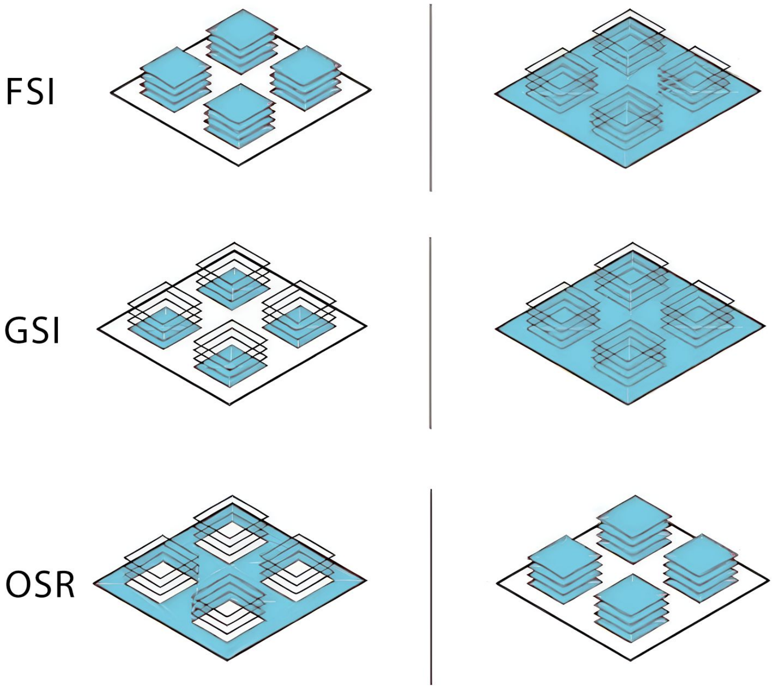
$$FSI = \frac{Gross\ floor\ area\ of\ all\ buildings\ in\ AOI}{Total\ area\ of\ AoI}$$

Ground Space Ratio

$$GSI = \frac{Total\ footprint\ area\ of\ buildings\ in\ AoI}{Total\ area\ of\ AoI}$$

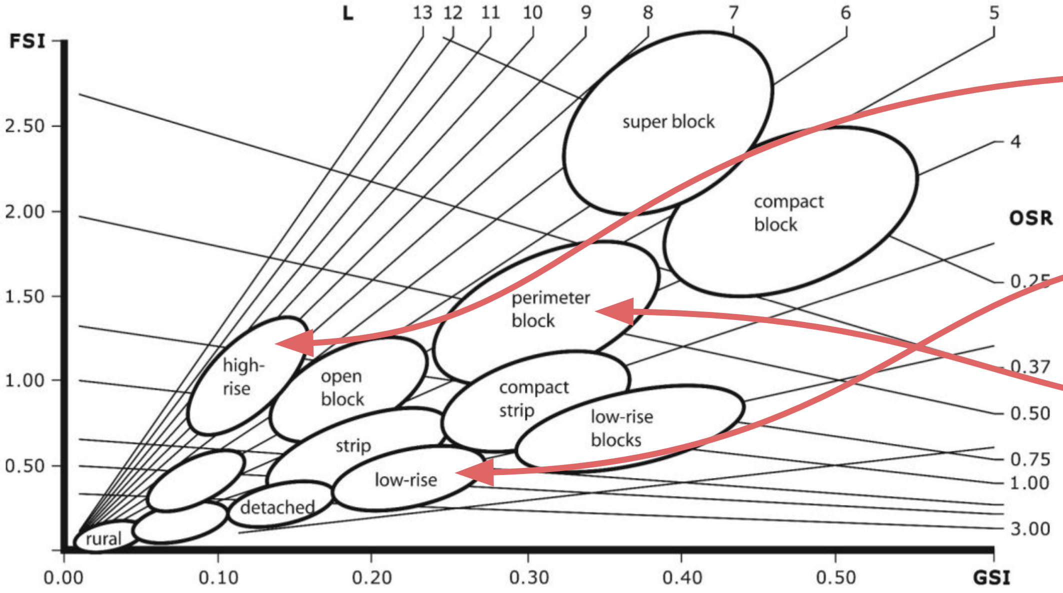
Open Space Ratio

$$OSR = \frac{Total\ area\ of\ non\text{-}built\ up\ surfaces\ in\ AoI}{Gross\ floor\ area\ of\ buildings\ in\ AoI}$$

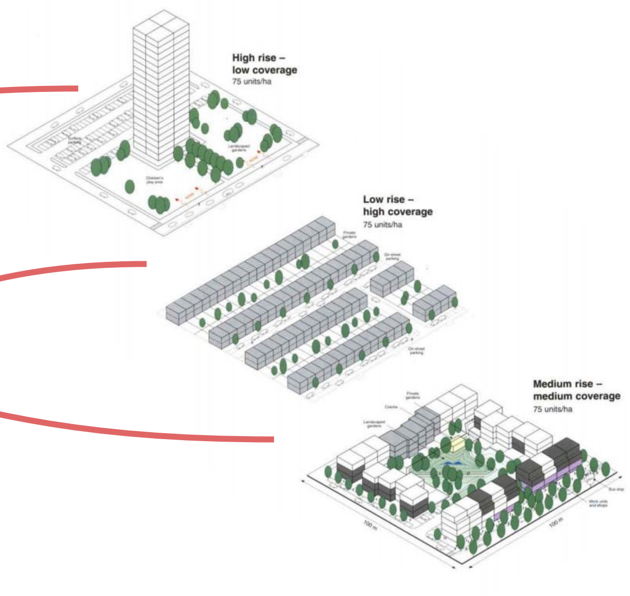


FSI, GSI, OSR (redrawn from Pont, M. B., & Haupt, P. [2007]. The relation between urban form and density.)

Spacematrix

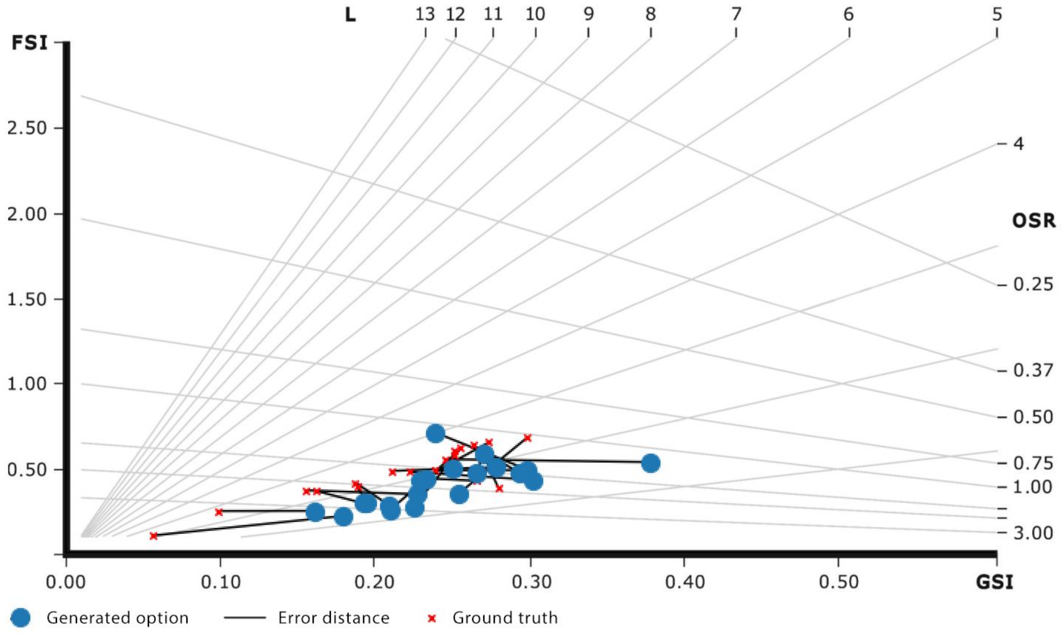


Urban morphological types mapped as their Spacematrix encodings (image from Pont, M. B., & Haupt, P. [2007]. The relation between urban form and density.)

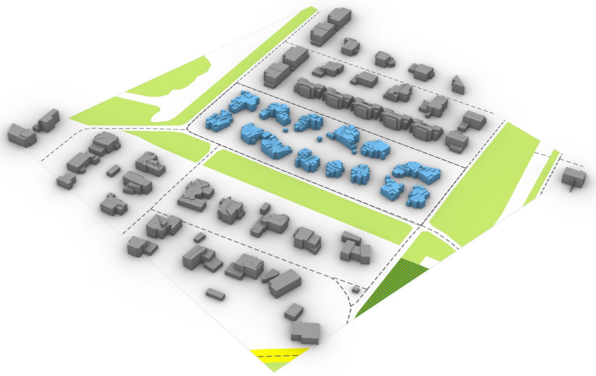


Urban morphological types for identical unit count (image from Richard Rogers [1999] 'Towards an Urban Renaissance')

Spacematrix

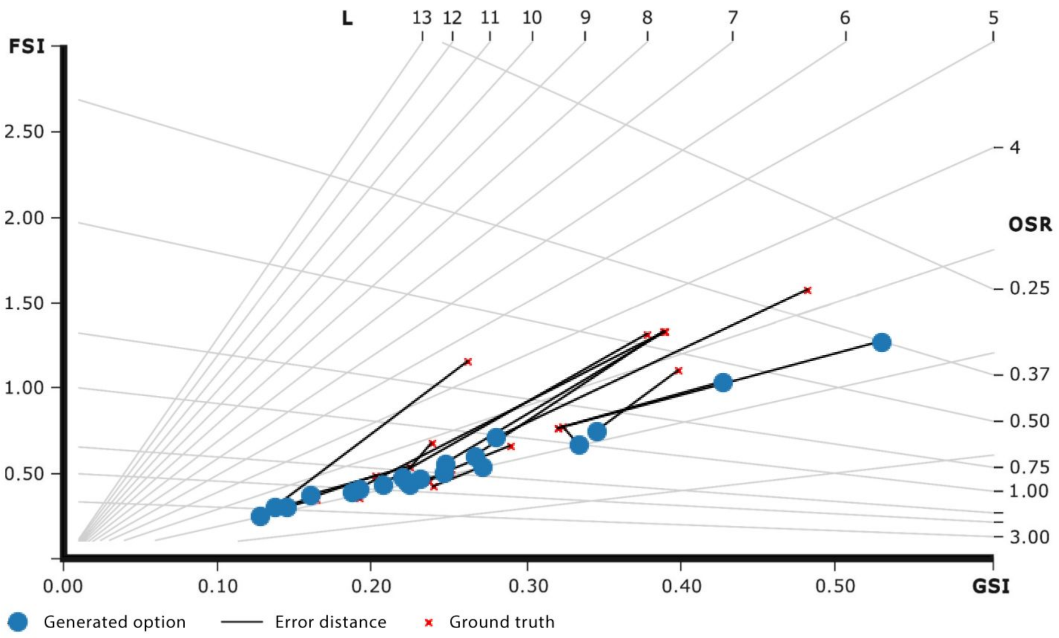


Results mapped as their Spacematrix encodings (plot template taken from Pont, M. B., & Haupt, P. [2007]. The relation between urban form and density.)

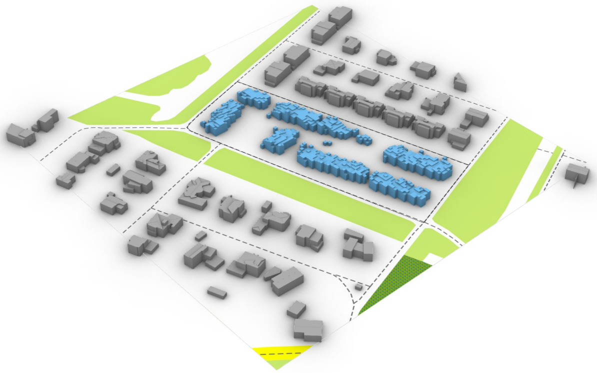


Results from experiment 2.

Spacematrix

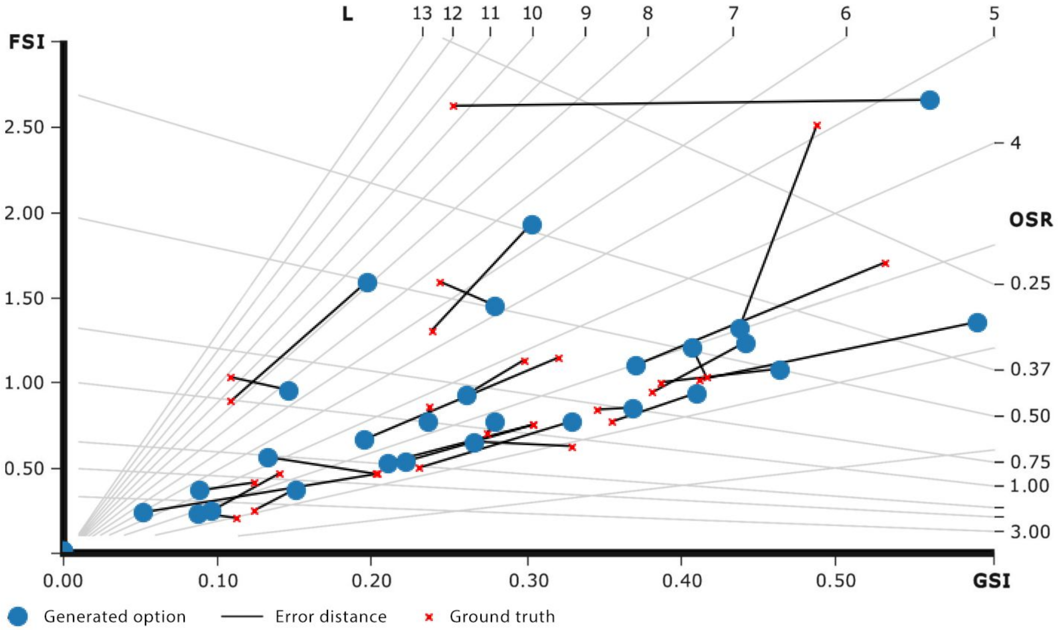


Results mapped as their Spacematrix encodings (plot template taken from Pont, M. B., & Haupt, P. [2007]. The relation between urban form and density.)

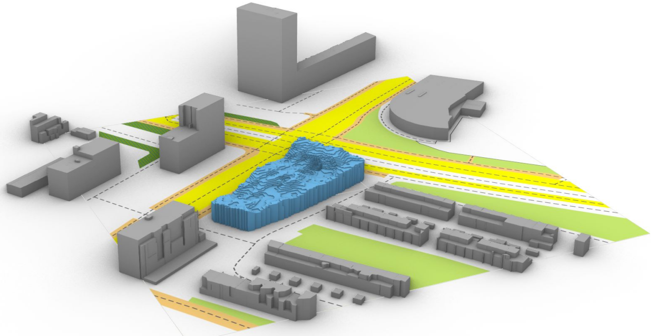


Results from experiment 3.

Spacematrix

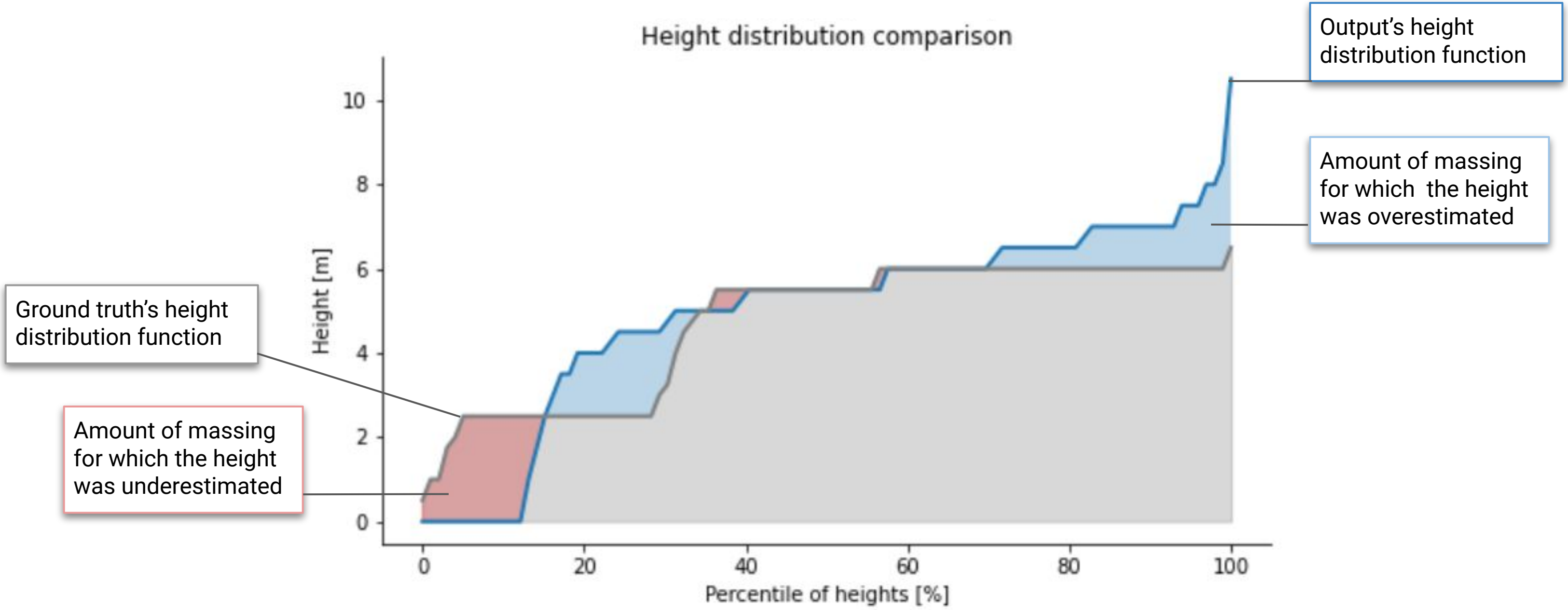


Results mapped as their Spacematrix encodings (plot template taken from Pont, M. B., & Haupt, P. [2007]. The relation between urban form and density.)

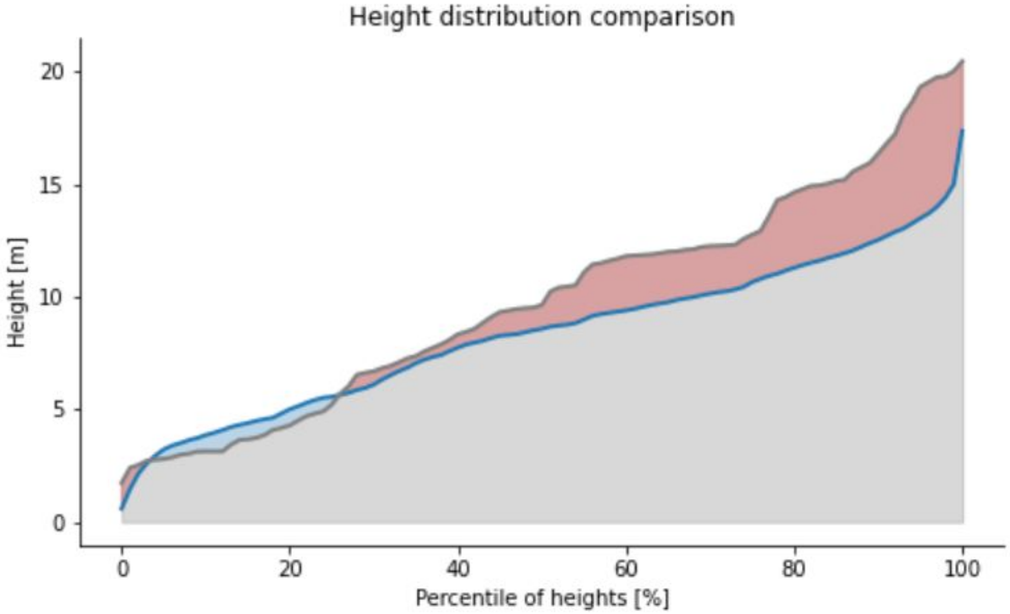


Results from experiment 5..

Height distribution

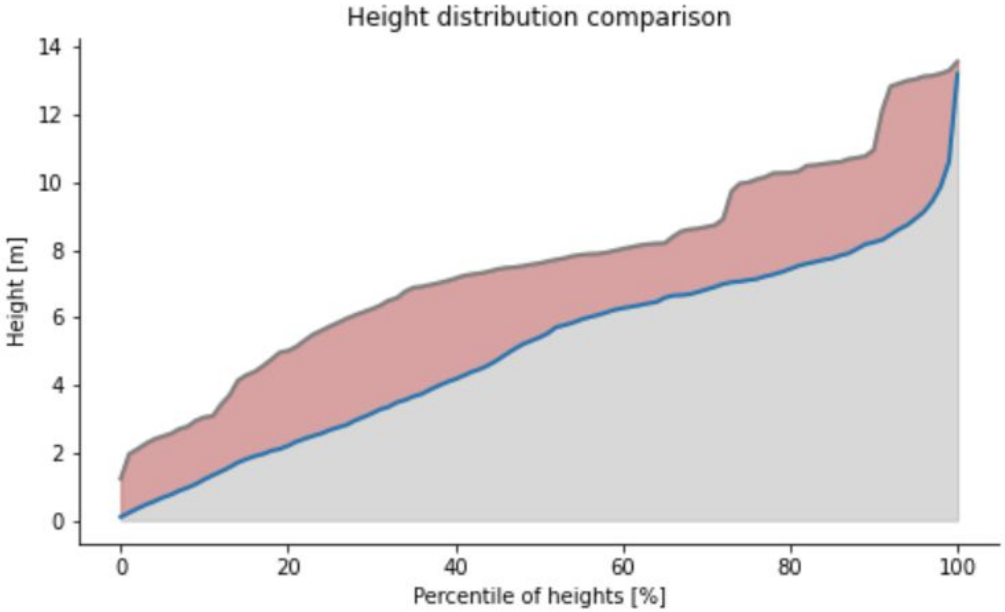


Height distribution



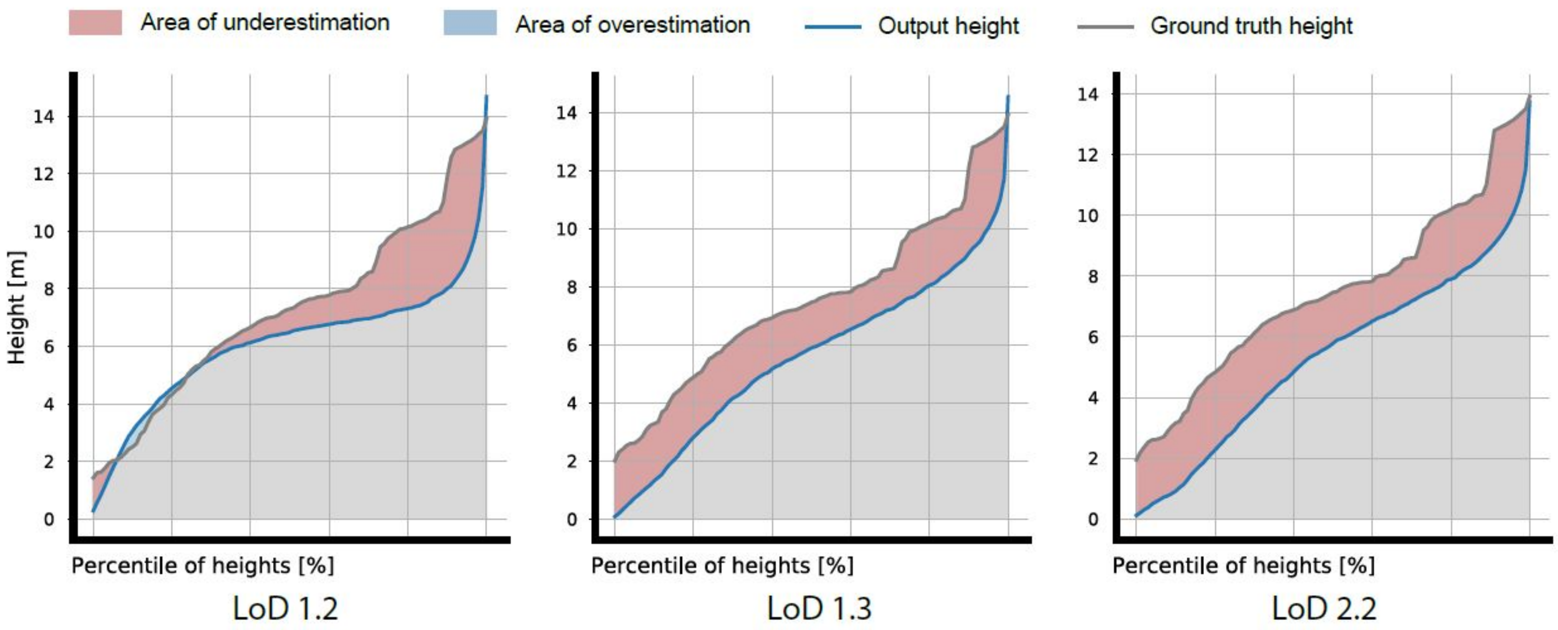
Results for 5th experiment - Office block generator

Height distribution



Results for 2th experiment - Residential street block generator

Height distribution



Results for 6th experiment - height distribution error compared to LoD 2.2

Model accuracy

	FSI	GSI	OSR
Ground truth (mean)	0.716	0.2734	1.291
LoD **1.2 (mean)**	0.593	0.2597	1.546
LoD **1.3 (mean)**	0.495	0.2296	1.743
LoD **2.2 (mean)**	0.516	0.2321	1.797
LoD **1.2 (**RMSE**)**	0.336	0.0698	0.569
LoD **1.3 (**RMSE**)**	0.332	0.0621	0.651
LoD **2.2 (**RMSE**)**	0.364	0.0711	0.788

Results for 6th experiment - Spacematrix prediction error compared to LoD 2.2

Research overview

What was achieved and what does it say about the research questions?

Results

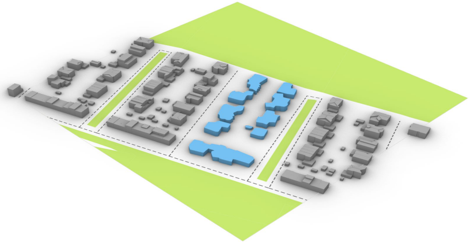
1. Implemented variations of the model for various use cases (single building, block, neighbourhood).
2. Tested different resolutions, scopes, and levels of detail of the training data.
3. Introduced two different method for conversion of the generated images into 3D.
4. Evaluated the typological similarity of the output to the ground truth.

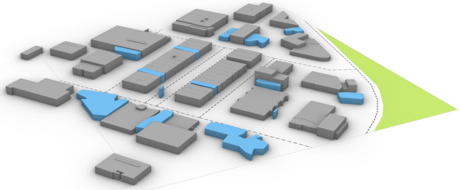
Research questions

At what **scales** is the method applicable (building, small block, larger site)?

?

All of them! I have applied the model at three scales and scopes, each with distinct goals specific to that scale.

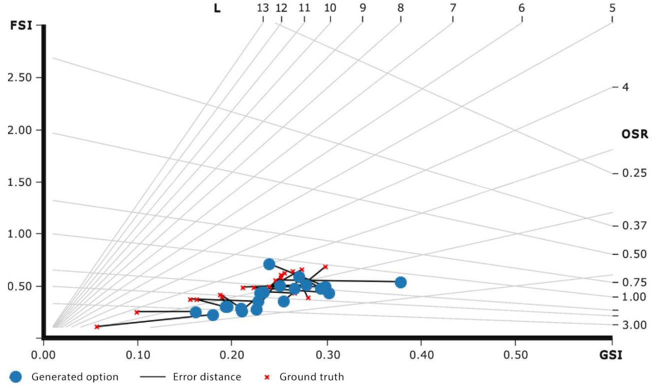




Research questions

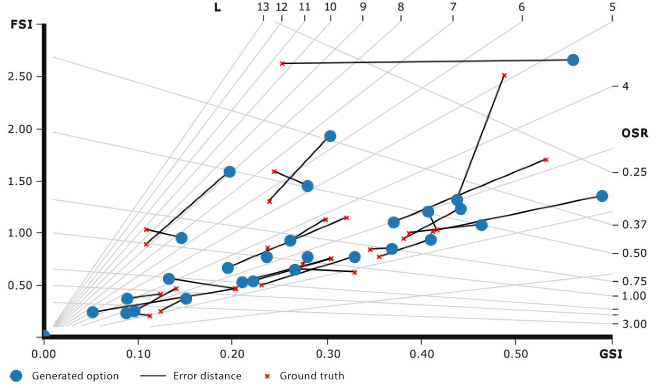
Can the model be **steered** towards certain typological **traits**?

?



Yes! Spacematrix mapping show that the distributions of the training data are replicated in the output of the model.

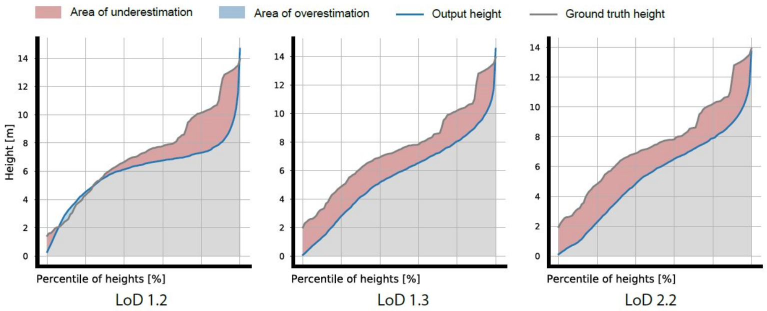
✔



Research questions

How important is the **level of detail** of the massing geometry and the included context?

?



	FSI	GSI	OSR
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LoD 1.2 (mean)	0.593	0.2597	1.546
LoD 1.3 (mean)	0.495	0.2296	1.743
LoD 2.2 (mean)	0.516	0.2321	1.797
LoD 1.2 (RMSE)	0.336	0.0698	0.569
LoD 1.3 (RMSE)	0.332	0.0621	0.651
LoD 2.2 (RMSE)	0.364	0.0711	0.788

Hard to say? Results obtained from the test are counterintuitive, could be related to dataset size. Required further research.

?

Research questions

To what extent can one **assist** the process of **building massing design** by utilizing **GAN model** trained on existing building forms?

?

... see last slides for more a more complex answer.

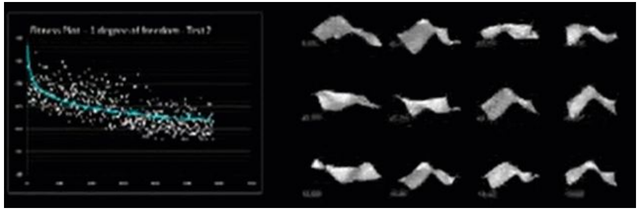
Contribution

What is the scientific relevance and potential applications of this research?

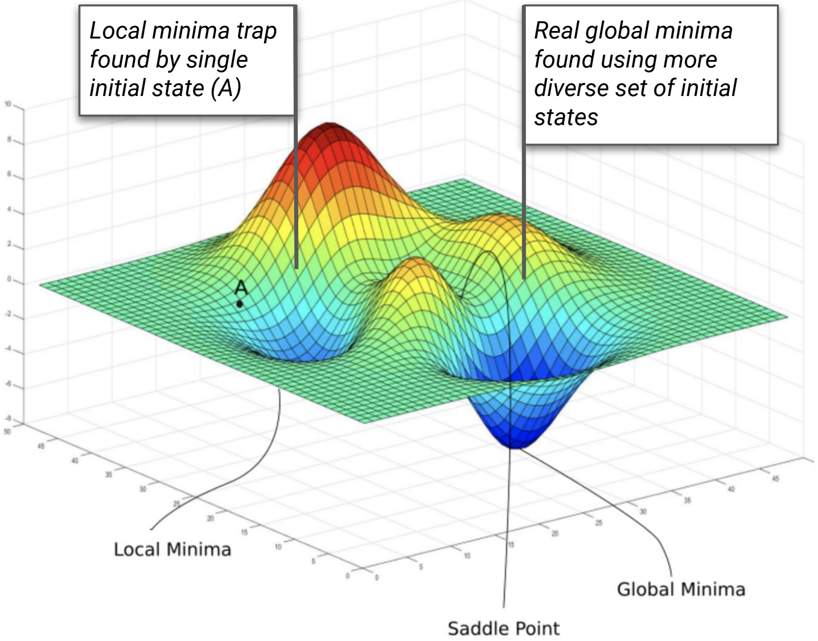
Optimization

A way to generate more diverse set of initial states for optimization algorithms

GAN proposed as a solution for avoiding local minima traps in NP-hard problems such as travelling salesman (Chen *at al*., 2019).



Angelos Chronis - Generative Fluid Dynamics: Integration of Fast Fluid Dynamics and Genetic Algorithms for wind loading optimization of a free form surface.



Yadav, P., 2021. Journey of Gradient Descent—From Local to Global. [online] Medium. https://medium.com/analytics-vidhya/journey-of-gradient-descent-from-local-to-global-c851eba3d367

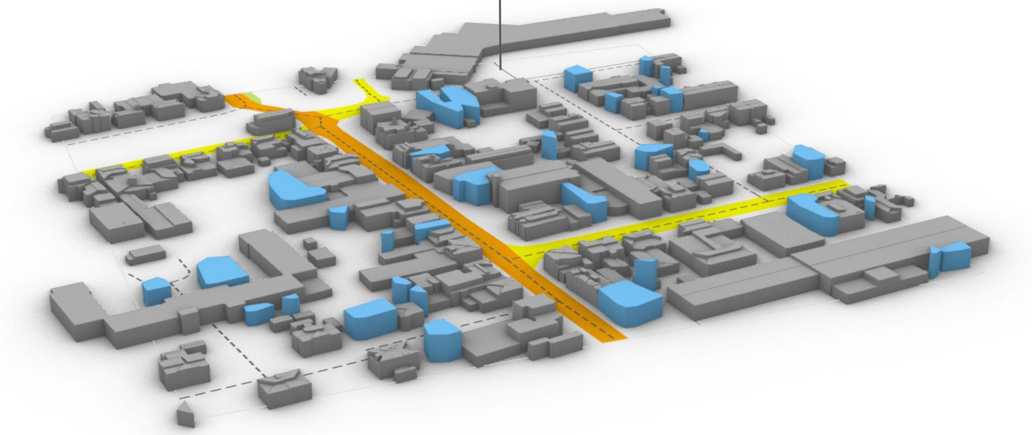
Analysis

Urban infill model as a densification potential analysis and exploration tool

Urban planners and municipalities could use the tool to explore and evaluate densification potential of urban areas.

Loibl, M. et al (2021) Effects of Densification on Urban Microclimate—A Case Study for the City of Vienna

Prediction of a potential densification scenario for an urban area



Design

Suggesting design exploration assistant for architects and designers

GANs have been previously used in design-centric human-computer interaction models (see Alonso, N., 2017 below).

Sketcher bot uses pix2pix trained on hand-sketches of trees and urban scenes (Suggestive Drawing Along Human and Artificial Intelligences, Alonso, N., [2017])

BIG City, exhibition, New York (Bjarke Ingels Group, 2007)
Available at https://www-architectural-review-com.tudelft.idm.oclc.org/essays

Demo

How could be such models integrated
in industry standard CAD applications?
youtube.com/watch?v=lbBTN7UndE0