MSc SBDE Title Page

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Module Title: Multi-Objective Design Optimisation

Coursework Title: Optimisation of modular facade
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Introduction

This coursework was based on Wates House case study building located in London. The intent was to explore alternative options for the south-west facade. The objective of the coursework was to give practical experience in framing and solving a multi-objective optimisation problem using 3D parametric modelling and environmental design tools. The focus was on geometry of the SW façade, material properties of the façade was not analysed in this study. The design had two conflicting objectives maximising natural light distribution and minimising total energy demand.

Rhino 6 and Grasshopper were used as a parametric 3D modelling tool with plugins Ladybug and Honeybee [4] within Grasshopper for energy and daylight simulations. The Octopus [5] was used for the optimisation process.

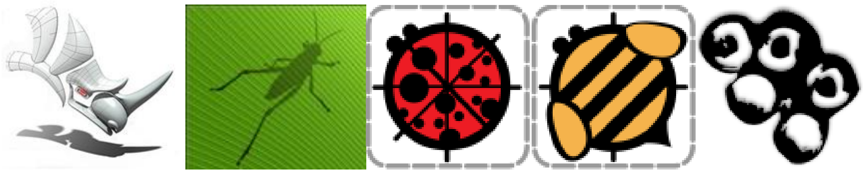


Figure 1 - From left to right. Rhino 6, Grasshopper, Ladybug, Honeybee and Octopus

My knowledge and understanding of the problem were changing during the process of creating a coursework. Design process of creating the coursework was iterative as each section: the understanding of the problem, modular facade concept and parametric model and finally objectives were changed.

Using octopus was optional and there were no additional points for using it. However, I concluded that knowledge gained from the lectures about evolutionary algorithms should be implemented in the coursework to challenge my understanding.

Understating the problem

Fragment from the coursework brief - „...the highest part of the facade is not shaded, and initial investigation have shown that the studio spaces on the upper floor were prone to overheating in the summer months. To minimise overall cooling energy demand, a shading strategy is to be developed for the SW facade.*"* [1]

Brief states that there is a problem with overheating in the summer months at the highest part of the facade and proposes to minimise overall cooling energy demand by shading strategy.

Using 3D model provided with the brief and Ladybug, total solar radiation received by the vertical SW facade over the summer period was calculated and presented to validate what was acknowledged during the investigation.

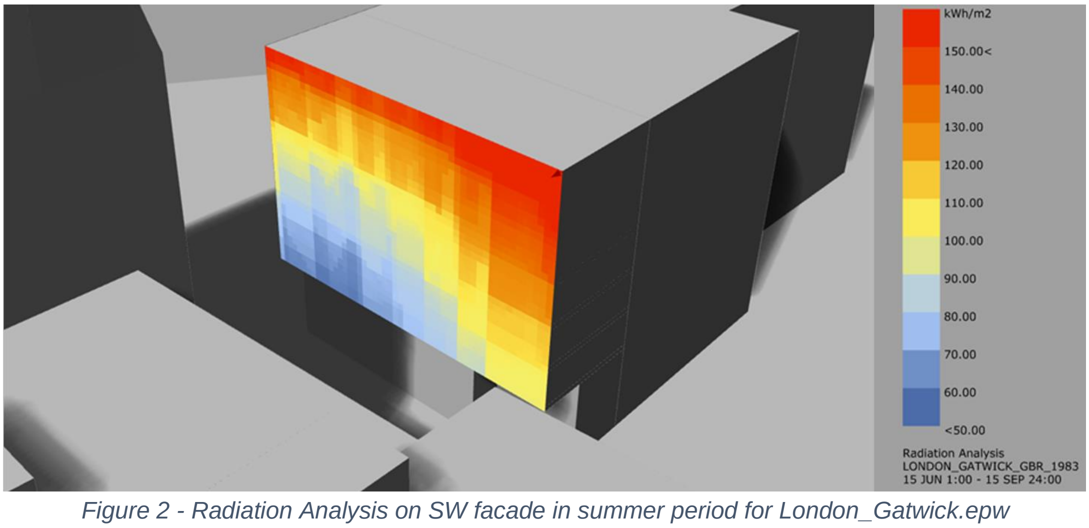


Figure 2 - Radiation Analysis on SW facade in summer period for London_Gatwick.epw

Second design driver was maximising natural light distribution. Using Honeybee daylight factor on each floor was calculated with four different glazing ratios for SW facade: 20%, 40%, 60% and 80%. Glazing on NW facade remained fixed as in the original 3D model.

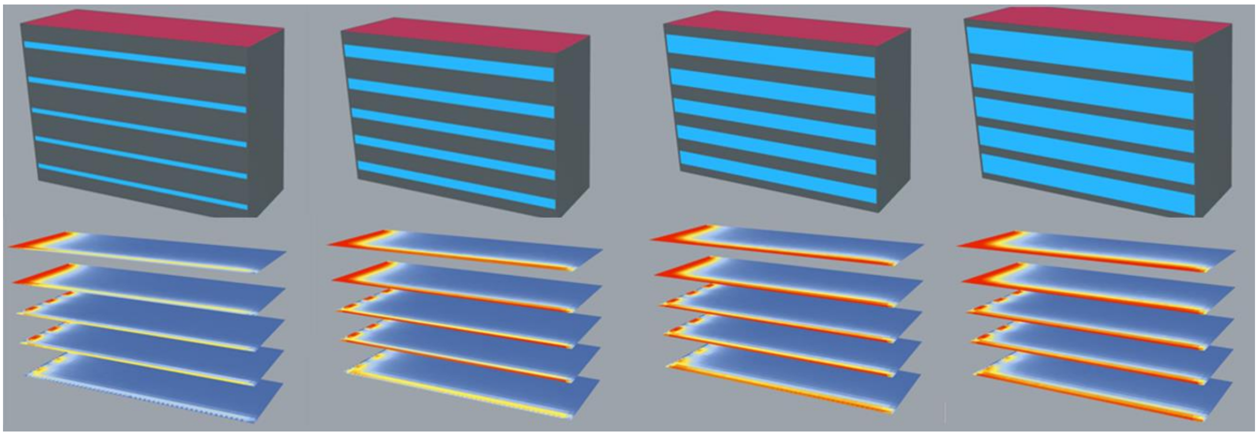


Figure 3 - Facades with four different glazing ratios and corresponding daylight factor maps

Three types of values were calculated and extracted from the models: cooling and heating demands that are supplied by ideal loads air system calculated with EnergyPlus v8.9 engine [6] in kWh/year and average daylight factor calculated on each floor. All environmental assumptions for calculations were taken from coursework brief [Appendix 1] Note: for the EnergyPlus simulation there was only one zone and for the radiance simulation there were five seperate zones.

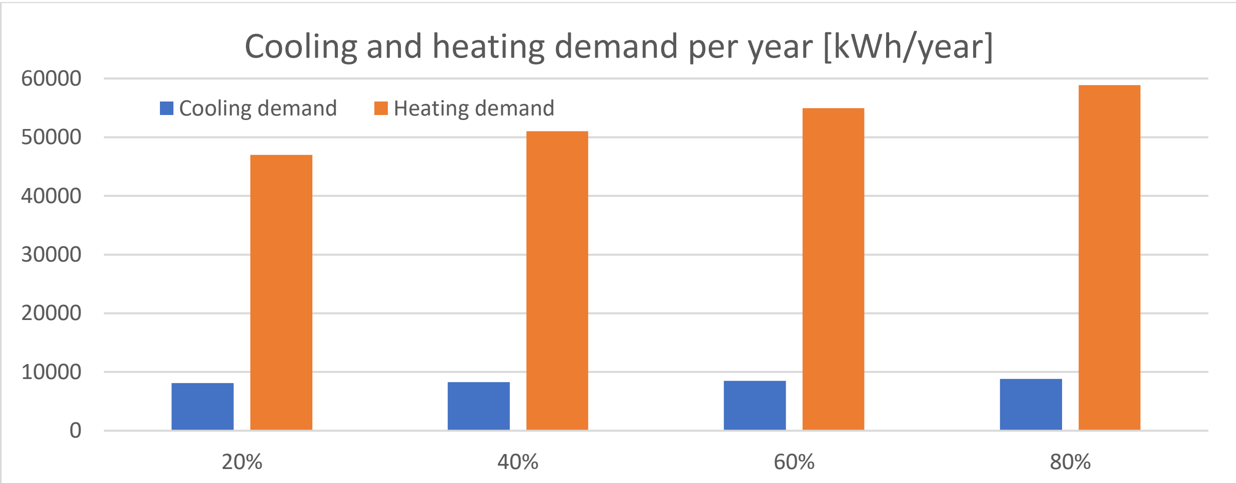


Figure 4 - Cooling and heating demand per year [kWh/year]

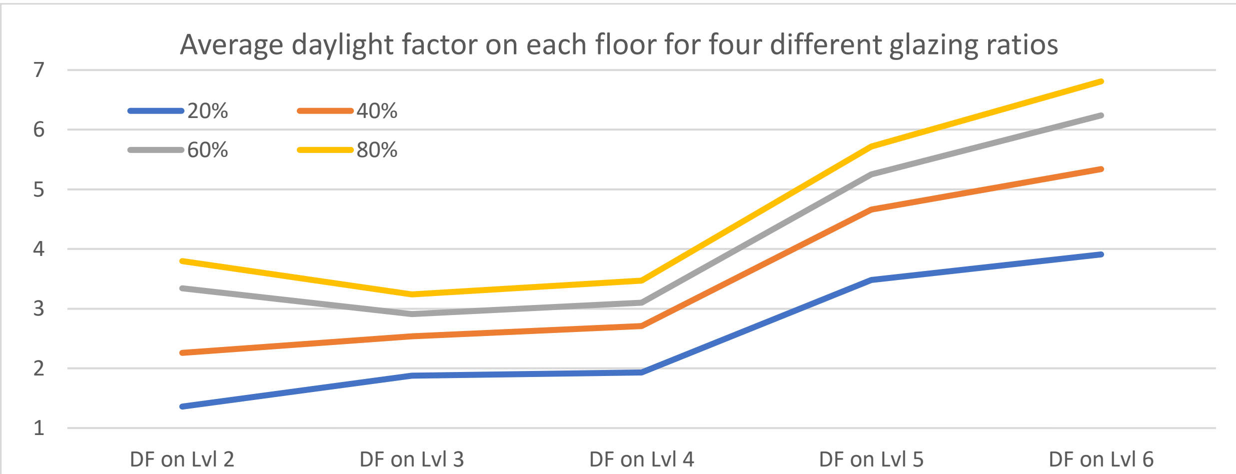


Figure 5 - Average daylight factor on each floor

Climate in London primarily demands heating as it has more heating design days then cooling design days.[2] Of course, it is subject to other parameters such as internal gains from equipment, number of occupants, schedules, setpoints etc. Looking just at the conduction and ventilation standpoint and knowing that the applied parameters from appendix 1 have quite high U-values the results are reasonable. What is also interesting is that increasing glazing ratio by 20% building demand for heating goes up by 4000 kWh and only by 150 kWh for cooling.

Before doing further sections of the coursework, there was important question to be answered. If I were to optimise the facade by placing the same window area, where would I put it? On the lowest level or on the highest level? Two optimisation aims described in the coursework brief in section 3: maximising the average daylight factor within the building and minimising the overall energy demand (heating + cooling) what would be the better solution? A or B?

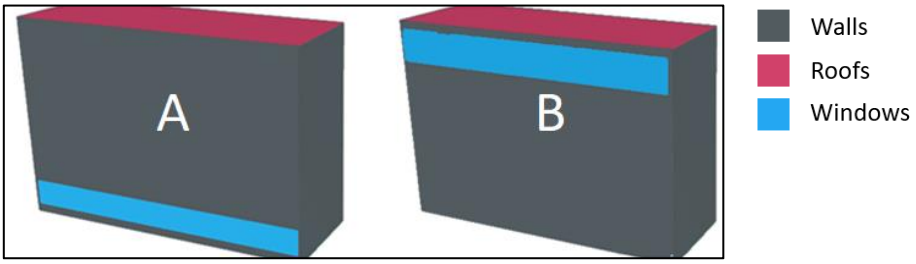


Figure 6 - Simple test A or B

My understanding was based on information about the model, made assumptions and generated results. From that I assumed that option B would be better solution for both objectives as building demands more heating than cooling and upper level is far less shaded by the surrounding buildings which results in both higher natural light levels and higher heat gains necessary for heating the building.

It is in contradiction to the specified problem of overheating on the highest levels. The objectives were not changed and parametric model with evolutionary algorithm optimisation was created so that the algorithm could validate my understanding.

In response to the question asked in the brief. Considering natural light and energy demand the appropriate glazing ratios on SW facade would be the smallest glazing ratio on the lowest floor and highest glazing ratio on the highest floor.

Development of modular facade concept and parametric model

For the algorithm to respond to the given question so that it can find good solutions it is important to create a parametric model that maps a given question. It should have high flexibility to ensure that the design space is big enough so it can „travel" and experience chosen solutions. But, of course, not too big. If there would be too many solutions, then many more simulations and generations would be necessary for the algorithm to converge.

The modular facade concept made from five principles:

1. variable panel count on each floor,
2. variable glazing ratio for each panel,
3. variable shading depth for each floor,
4. variable location of the transparent part on panels,
5. variable panel width for each panel.

This concept was translated to the geometry inside grasshopper with mathematical functions and number slider as the function's coefficients with the corresponding bounds so that the models can be simulated with Honeybee plugin.

Principles 1,2,3 are controlled with linear functions y=ax+b, 4th have only three options {left, centre, right}, 5th principle is a combination of the two sine functions, so that it will create high variability and flexibility. Total pool of possible solutions $1.3*10^{13}$.

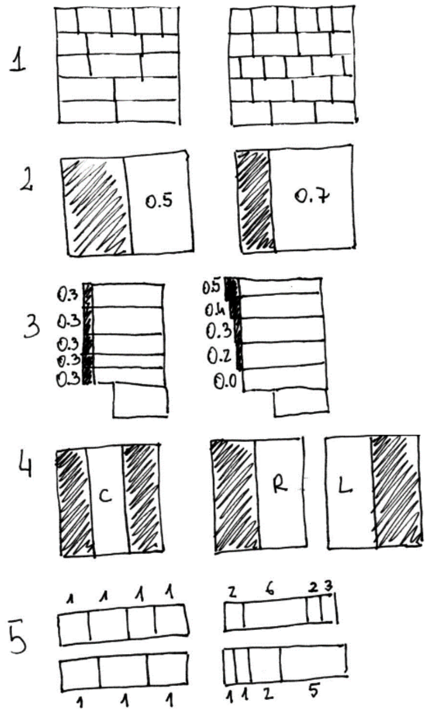


Figure 7 - Concept sketches for parametric facade

Manually generated examples of parametric facade that follow all defined principles.

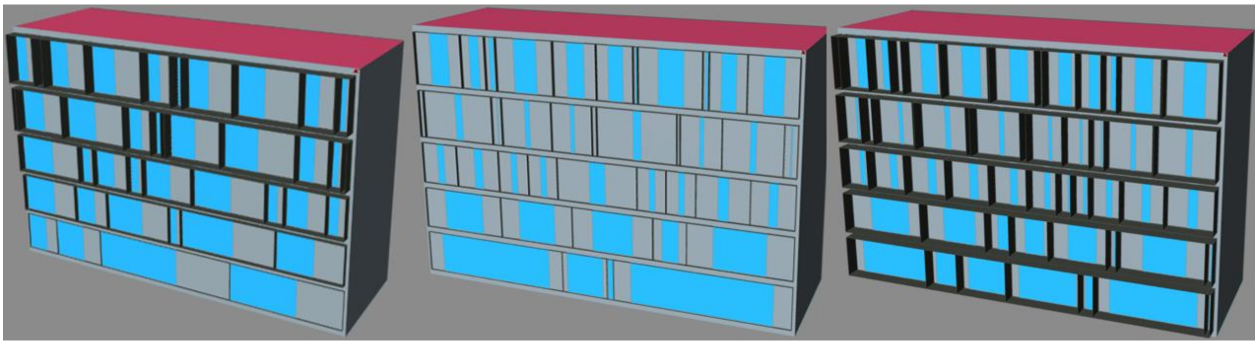


Figure 8 - Three examples of parametric facade that follow all defined principles.

Although whole script in Grasshopper is made of many nodes and may look too complicated.

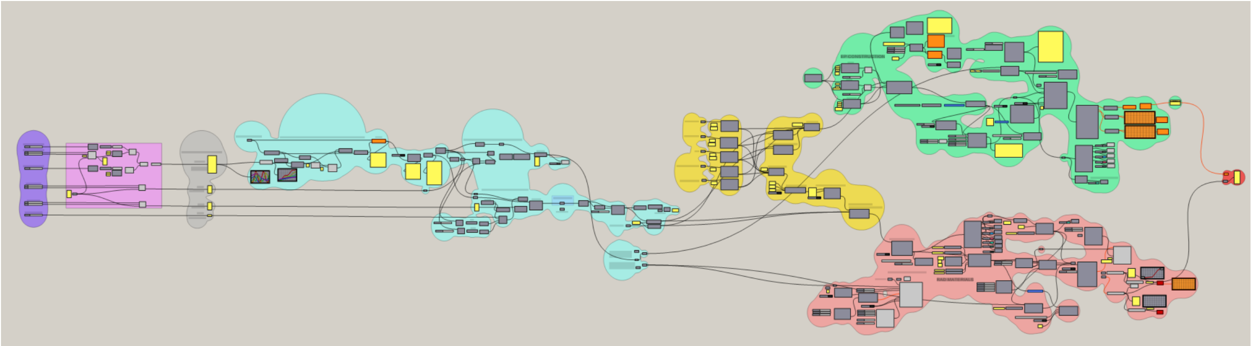


Figure 9 - Screenshot of grasshopper script

General idea behind the whole script is very simple and is presented below.

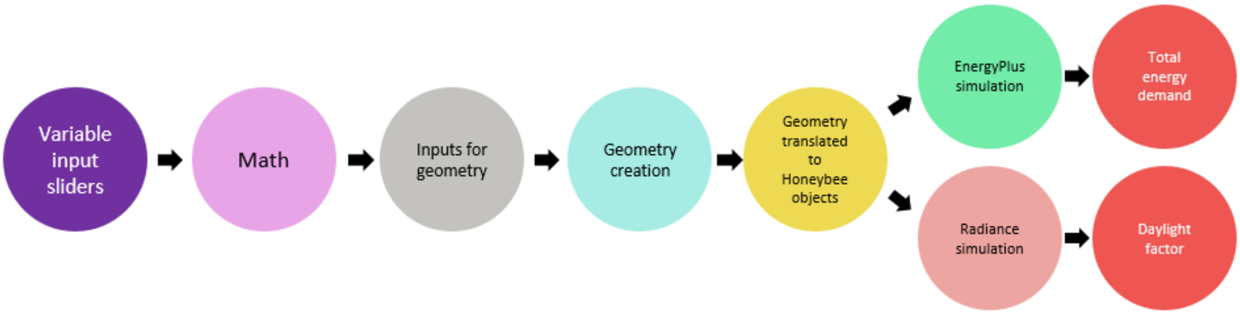


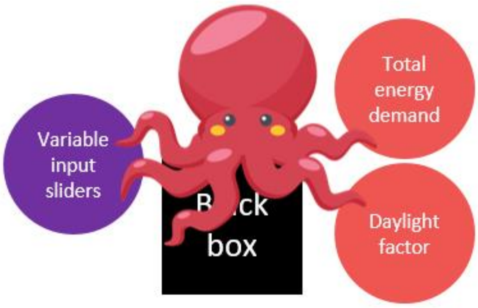
Figure 10 - General idea behind the grasshopper script

Variable input sliders are coefficients for math functions that create lists of values necessary for modelling geometry. Geometry is created as simple surfaces which is transferred to flat elements of windows and opaque shading elements which are translated to the honeybee objects. Honeybee objects are then processed into two seperate paths, where first one adds energy plus assumptions such as construction features (U-values, infiltration, g-value that meet ASHRAE 90.1-2010 standard for climate zone 7-8), internal gains from lighting, equipment and people with its corresponding schedules, setpoints for heating and cooling. Second path adds radiance assumptions such as radiance material properties, zone test points, daylight factor recipe. Simulation parameters are then extracted from the analysis as two seperate numbers: total energy demand and average daylight factor which can be later easily supplied to the optimisation plugin octopus.

Testing and running optimisation algorithm

What is beautiful about evolutionary algorithms is that they don't need to understand functions, relationship or logic that is between inputs and outputs, it can be unknown black box for them. Octopus just needs to have information about inputs and outputs, and it will try to optimise our multi-objective design question.

Our previous graph can be simplified even more as optimisation tool Octopus only needs inputs and outputs to perform its task.



Optimisation was tested on small batch to see what the average simulation time for a single model was. Input bounds were set and checked so they would not exceed real dimensions and simulation would not crash during the optimisation process. Average time of a single model was around 33 seconds, which meant that the optimisation process could run during the night and would yield almost 900 models in 8 hours.

Review results and discussion

To maintain low simulation times for EnergyPlus and Radiance certain simulation parameters where changed to trade-off quality for time, which are described in more detail in appendix 1.

First optimisation run was stopped after 41 generations and it successfully converged around 10th generation. Simulation was not stopped at 10th gen as it was simulated during the night. Average time was around 25 seconds for a single simulation. Optimisation parameters were population size 30, elitism 1, mutation probability 0.2, mutation rate 0.05, crossover rate 0.8, HypE reduction and HypE mutation. Red dots are three examples of solutions from Pareto front. All optimisation runs were set with the same optimisation parameters, they were not changed as algorithm was able to converge in time limit of one night for a single optimisation run.

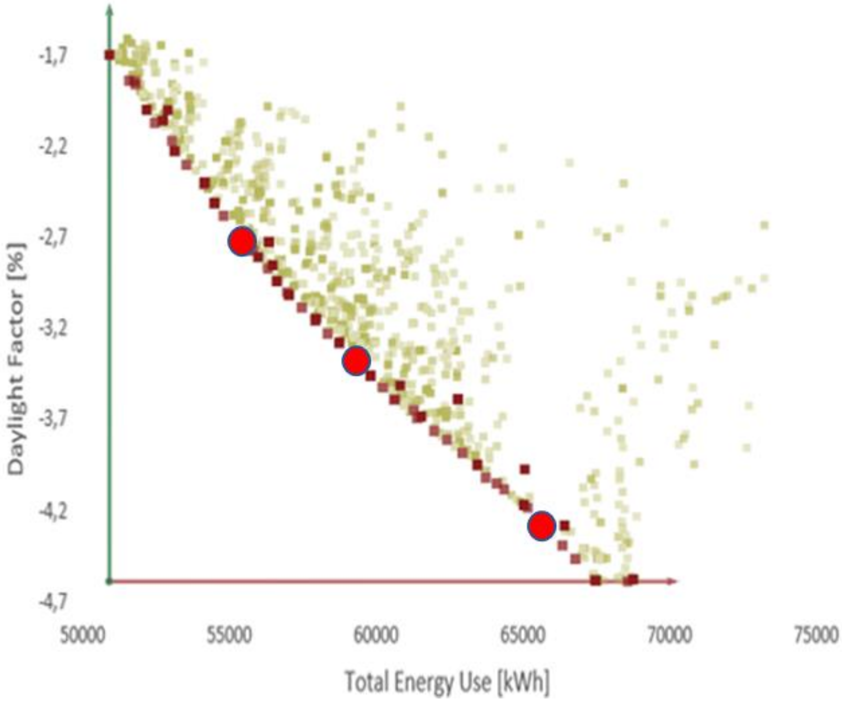


Figure 11 - All generations for first optimisation run

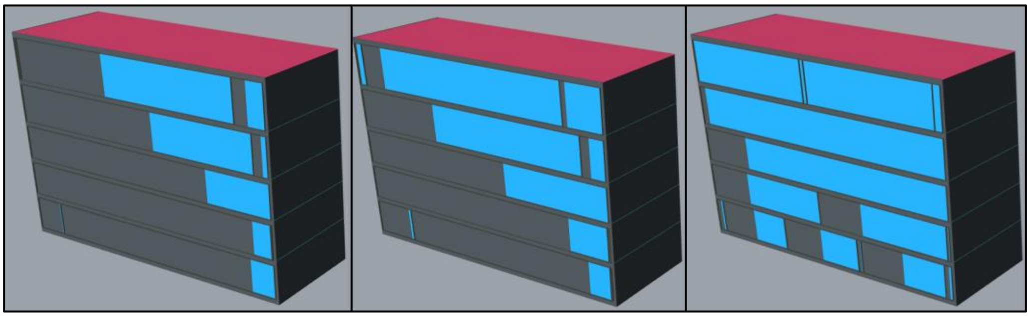


Figure 12 - Three solutions from pareto front from the first optimisation run

Total energy use [MWh]	56	59	67
Average daylight factor [%]	2.72	3.31	4.35

Two main conclusions after first optimisation run are that the algorithm completely removed shading and put more glazing on top right corner. This confirms assumption from “understanding the problem” section that option B would be preferred solution.

Daylight distribution with shading would obviously be worse than without. To see how shading affects the total energy objective - small test was created with two models, one with shading and one without. Removing shading adds 1200kWh of cooling and removes 4200kWh of heating. Shading in parametric concept was not revised as first optimisation runs completely removed shading, other aspects of the design was revised such as objective functions and window geometry.

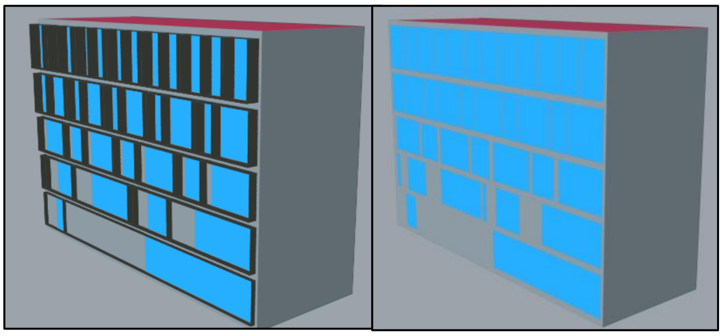


Figure 13 - Facade with and without - total energy demand test

During "design crit" it was said that mean average of daylight factor values from the grid of points is not the best function for "Maximising the distribution of natural light". Another function was proposed by the lecturer – percentage of the area that has daylight factor above certain threshold. For second and third optimisation run, new post processing method for the daylight factor was implemented, threshold was set to 3%.

Second optimisation run with new daylight objective gave slightly different results. In total 48 generations were created with the same optimisation parameter settings. Still overhangs or vertical fins almost did not exist, but the number of panels on each floor was slightly different. Now algorithm tried to find more even distribution of natural light on each floor.

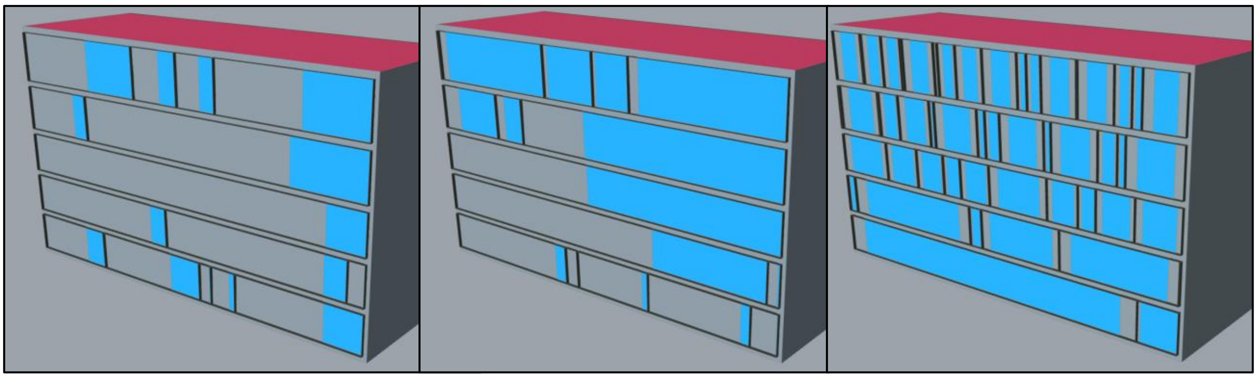


Figure 14 - Three picked solutions from pareto front from second optimisation run

Very small window widths appeared in multiple locations in both first and second run. Two sine functions added a lot of possibilities and flexibility but unfortunately it added also too much noise. Fifth principle - variable width of the panel was removed from the parametric concept to simplify the design, make it more consistent and aligned.

In exchange for variable width new rule was added - variable height of the window. This should have enabled better daylight distribution with smaller window area.

Third optimisation run was set with different parametric model concept, but with the same optimisation parameters and the same number of generations as the second run 48 in total.

Elites from the last generation – 48th for second and third optimisation runs are presented below. First optimisation run could not be plotted on this chart as function calculating the objective for daylight was different.

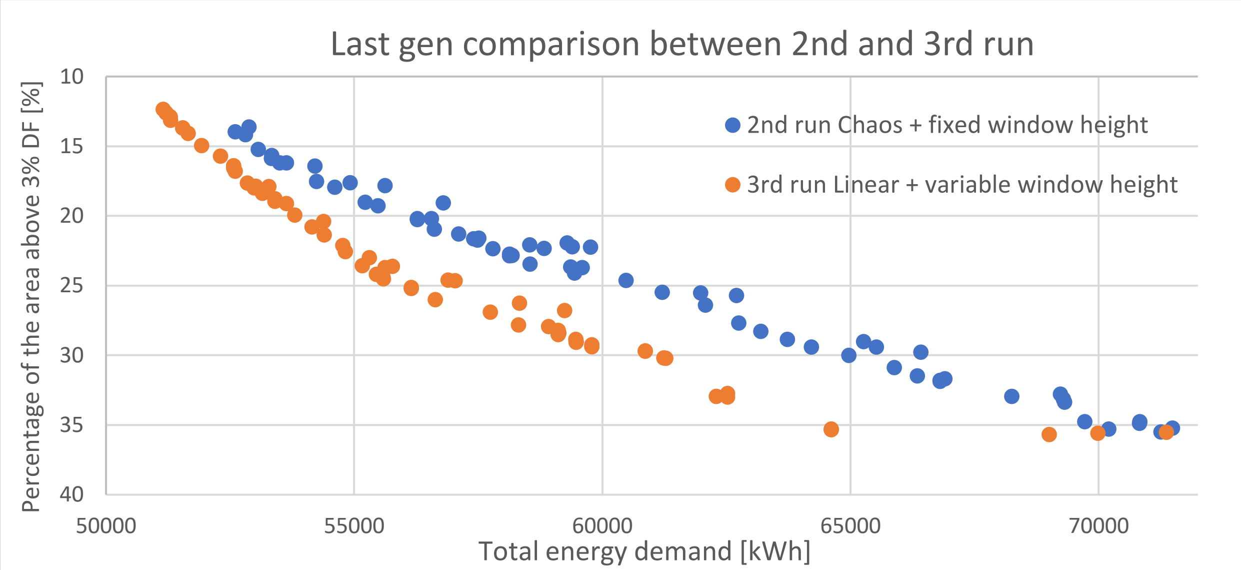


Figure 15 - Solutions from last generation comparison between 2nd and 3rd run

Simplified model and variable width exchanged for variable height resulted in better performing results after the same number of simulations being generated.

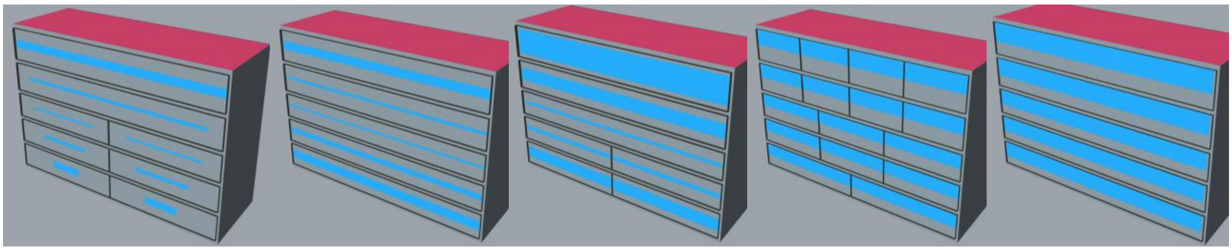


Figure 16 - Few examples from the pareto front from the 3rd optimisation run

To obtain results that will fit our problem we need to revise what do we want to optimise. Asking the right question is very important when using evolutionary algorithms.

Do we want to optimise total energy use or maybe we want to optimise for overheating? If so, then we need to define what is overheating and construct the model in a way that would make it possible for evaluation. We can define overheating as predicted mean vote (PMV) from Fanger model and ASHRAE standard 55 [3] to minimise number of hours when PMV would be above +1. We would then need to make few more assumptions such as clothing level, metabolic rate, wind speed inside the zone. Additionally, we would need to split our single zone energy model into five separate zones, so we could have better information about surface temperatures and average radiant temperature inside each zone.

Methodology for completing the coursework was similar to the design thinking approach. Normally design thinking consists of five steps: empathize, define, ideate, prototype and test which typically is an iterative process. In this coursework methodology from the lecture was used:

1. Recognize the question
2. Defining the strategy
3. Creating the model
4. Performing Calculations
5. Choosing related data
6. Results visualisation
7. Interpreting the simulation results
8. Modyfing the design alternative

My understanding of the problem, assumptions, objectives changed from the beginning to the end of the design. If I were do this coursework once again, I would change total energy demand objective to PMV objective and many more aspects of this coursework.

Unfortunately, we are typically limited by resources such as time, budget, tools, hardware but also very often by our understanding of the researched topic. We struggle to make better design decisions and with tools that enable us to model all this in virtual environment we can learn faster so that we can make better design decisions.

References

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4. Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally conscious design. [online]. Available from: http://www.ibpsa.org/proceedings/bs2013/p_2499.pdf
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Appendix 1 – Guidance on modelling methods and parameters

Calculations of Section 1

Solar radiation plot on SW facade

- Take whole façade surface to generate grid – ensure normal vectors point outward – ie towards the Southwest. This can be checked using the vector visualisation tool in Grasshopper.
- Grid size parameter: 0.5m
- Distance from base: 0.01m
- Model should include surrounding buildings
- Model should include ground plane
- Ladybug parameters:
    - Use London Gatwick Weather file (.epw)
    - Use a Sky Density of 1
    - Include diffuse and direct radiation
    - Analysis period of 15 June – 15 September
- Make sure that the results are sensible with more solar radiations received in the upper part of the façade.
- 'Bake' the results in Grasshopper to create a mesh object within Rhino.
- Render the façade with some of the context. Ensure you add a key and legend to the render.

Daylight calculations

- Develop a daylighting model in Grasshopper from the surfaces in the Rhino model.
- Generate analysis grid for each floors (2 to 6 only). This study only focuses on the SW end of the building and floors 2 to 6. Analysis grid to be generated 0.8m above floor level. Grid size parameter: 0.5m. Ensure normal vectors point up. This can be checked using the vector visualisation tool in Grasshopper.
- Model should include surrounding buildings and ground plane, use '*Context_Material*' as material.
- Glazing material: *HB Glass Material with average transmittance of 0.8 and refractive index of 1.52*
- External walls and roof material:*Context_Material*
- Interior wall: *Interior_Wall*
- Ceilings material: *Interior_Ceiling*
- Floor materials: *Interior_Floor*
- Honeybee parameters:
    - Use London Gatwick Weather file (.epw)
    - Use Cloudy Sky
    - Radiance parameters: -ab 2 -ad 1000 -as 20 -ar 300 -aa 0.1
- 'Bake' the results in Grasshopper to create a number of mesh objects within Rhino.
- Render with some of the context. Ensure you add a key and legend to the render.

Annual heating and cooling energy demand calculations

- Develop a single zone thermal model in Grasshopper from the surfaces in the Rhino model.
- Occupancy: 1 person per 12m^2
- Lighting load: 10 W/m^2
- Equipment gains: 10W/m^2
- Air infiltration: 0.2 ACH
- Ventilation rate: 10l/s per person
- All zone schedules (occupancy, heating set point, cooling set point, lighting, equipment) from Zone Program: *Office:OpenOffice*
- Use London Gatwick Weather file (.epw)
- Time steps per hour: 4
- Solar distribution: FullExteriorWithReflections
- Terrain type: *City*
- Shadow calculation method: *default (AverageOverDaysInFrequency)*
- Shadow calc frequency: 30

- Shadow calc overlap: 15000
- You may either develop custom assembly for walls and roofs, and double glazed clear glass windows with low-E coating to meet Part L requirements for U-values. Alternatively you may use the following default constructions: *ASHRAE 90.1-2010 EXTROOF IEAD CLIMATEZONE 8 SEMIHEATED , ASHRAE 90.1-2010 EXTWALL MASS CLIMATEZONE 7-8 , ASHRAE 90.1-2010 EXTWINDOW NONMETAL CLIMATEZONE 7-8*

Calculations of Section 3

To speed up daylight factor calculations, use Radiance parameters: -ab 2 -ad 650 -as 50 -ar 180 -aa 0.1

To speed up thermal calculations, use:
- time step per hour = 2,
- Solar distribution = 'Full Exterior',
- shadow calculation frequency = 40
- shadow overlap = 1,000.

There will be a loss of accuracy but should be a very significant gain of time.

If using Octopus:
- Initial simulations: use a population of 20-30
- Final simulations: use population of 60-80…. You can go up to 100, if model runs fast enough.
- Elite size=population size
- Mutation rate 5%