

EARLY STAGE OPTIMIZATION TOWARDS A CLIMATE RESPONSIVE DESIGN

Building Technology Master Thesis

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- 1.1. Context
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1.1. Context

Global Situation

Climate change is having a significant impact on the planet with more extreme weathers present at a higher frequency rate. This is exacerbated by the constant use of fossil fuels for energy production at a global scale, with just under 95% of global energy coming from non-renewable resources (IEA, 2022).

The world's burning of fossil fuels releases around 40 Gt of CO₂ equivalent emissions into the atmosphere (IEA, 2021) and although there are agreements and directives to reduce global emissions by 2050 there is no definitive pathway towards a net zero energy scenario.

Some countries have implemented renewable energy sources as a means of mitigating climate change, pollution and to improve their energy security concerns. Norway, for example, supplies 97% of its electricity from hydropower whilst Paraguay supplies 100% from hydroelectric (US EIA, International energy statistics data for 2011).

By 2050 it is expected for 68% of the world population to live in urban areas (United Nations, 2018), leading to denser cities and new building projects. High rise buildings will become a necessity as housing demand and the need for commercial centers increases.

Building Context

Commonly built with a combination of steel and concrete, traditional high rise buildings are not climate-responsive. Their construction is focused on immediate needs with little regard to the climate's systemic changes. Their comfort is offered through active systems; heating, ventilation, air conditioning, lighting, soundproofing structures and ergonomics as a means of improving occupants' quality of life (Irfeey et al., 2023).

The built environment is an essential part of human lives as we spend 80% to 90% of

our time indoors (Hoppe, 2002). Building performance, especially energy efficiency, accounts for a large part of the world's energy consumption – around 40% of the total energy consumption (Amasyali, 2018).

Economic Impact

There is a desire at all decision making levels to shift towards renewable energy sources as a means of combating climate change. Such a transition is not always possible due to the lack of technical knowledge or financial capability, leaving many to 'business as usual' by utilizing fossil fuels for heating and relying on national electricity grids for cooling and energy consumption.

In order to comply with the European Green Deal directives, all new constructions in Europe shall aim towards a near-zero energy consumption target. Such requirements place pressure on individuals which have limited resources towards their home design and development.

Energy poverty is recognized as a major issue in a European context (Economidou M et al., 2023) and is definitely present in countries, especially third world countries, all around the world where people are not able to adequately heat or cover their basic energy services.

Energy Hierarchy

If the energy hierarchy pyramid is followed, the initial stage towards mitigating global emissions is to reduce energy consumption. The Energy Hierarchy indicates five priority levels which assist in the development of a more sustainable energy system (Institution of Mechanical Engineers, 2009).

Energy Saving focuses on conserving or avoiding unnecessary energy use. This ranges from lighting consumption to building insulation as a means of reducing energy losses.

Energy Efficiency relates to the use of efficient equipment such as lighting fixtures and appliances.

Renewables is the use of renewable energy sources towards energy generation such as wind, sun, waves, tides, geothermal or hydropower. It's the energy sources which do not require combustibles to function.

Low Emission Energy Production is not entirely renewable but has a low environmental impact such as nuclear power.

Conventional Energy Production is linked to fossil fuel sources.

Prioritizing the energy hierarchy as a decision framework reduces waste and improves efficiency, being a close link to sustainable development principles. Sustainability embraces social, economic and environmental impacts with the objective of improving human's lives without risking resource depletion, "meeting the needs of the present without compromising the ability of future generations to meet their own" (UN Brundtland Commission, 1987). Energy policies, following energy hierarchy principles, aim to reduce energy use prior to seeking methods towards supplying remaining demand.

Global Investment Priorities

Although there is a need to curb global emissions, the global investment strategy does not reflect the energy hierarchy's priorities with investment going mainly towards energy infrastructure, power generation and fuel production (IEA, 2017). Global investment strategies reflect a greater investment in renewable energy production instead of energy savings as a method towards CO2 emission reduction. The energy hierarchy is therefore skewed towards a more expensive, less accessible and less efficient method when addressing energy consumption and thus, less efficient at curbing CO2 emission levels.

In order to reduce energy consumption in new constructions it is necessary to address the energy hierarchy from the top, therefore reducing operational costs and the need of investment into technological solutions in the future. Within the building sector there is a need to reduce energy consumption, reducing CO2 emissions, minimizing operational costs and improving interior comfort levels.

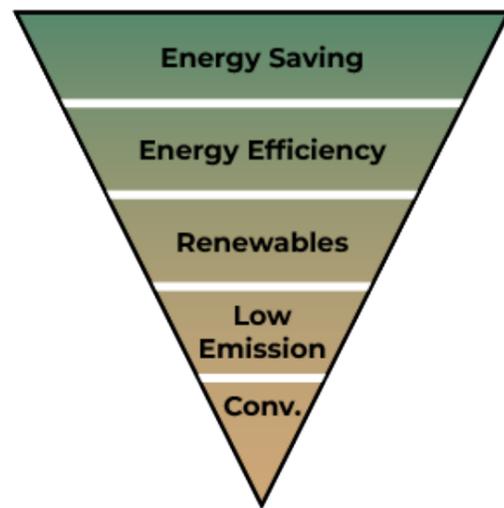


Fig 1: Energy Hierarchy based on information from the Institution of Mechanical Engineers, 2009

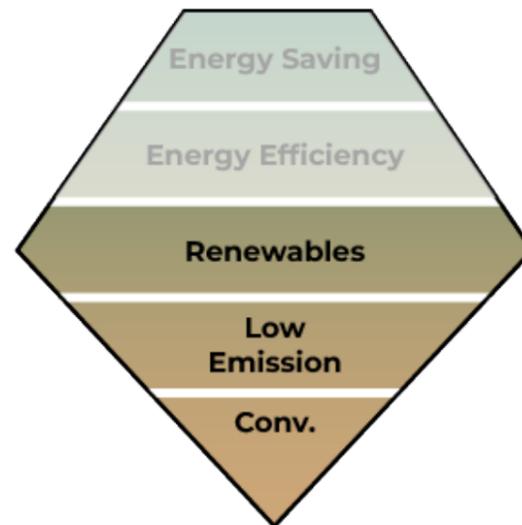


Fig 2: Modified Energy Hierarchy based on current global investment

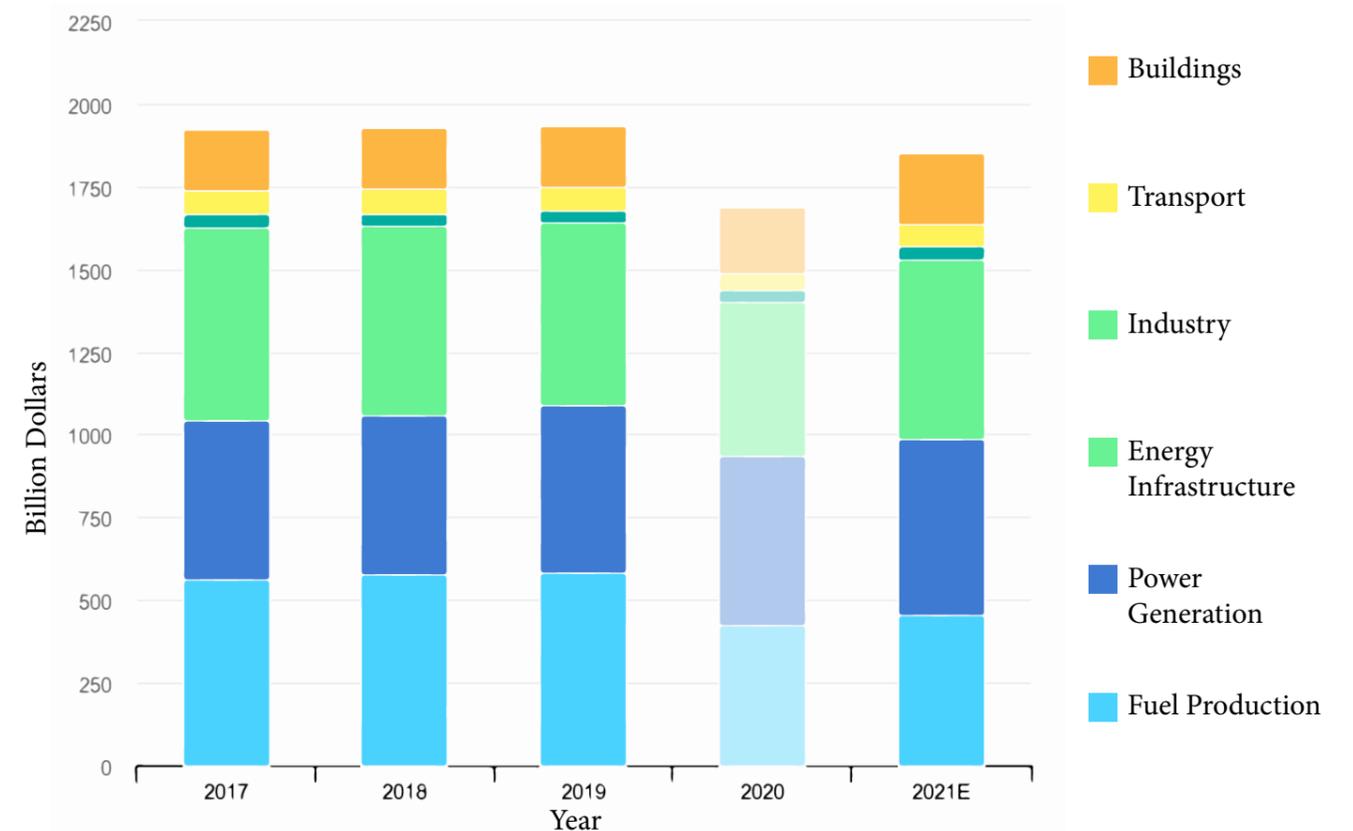


Fig 3: IEA, Global Energy Investment, 2017 - 2021

1.2. Problem Statement

Energy consumption has been increasing steadily and will further increase as the world population grows. Governments and organizations have devised pledges and agreements towards reducing CO2 emissions to curb the effects of climate change.

Building simulations point towards effective solutions in reducing a project's energy consumption. However, these simulations require specialized knowledge and are often implemented late in the design process, reducing their effectiveness and increasing project costs.

Objective

The aim of this study is to determine an effective optimization workflow towards the implementation of passive design strategies to guide the design process from an early design stage. Qualitative and quantitative methods will be used to identify passive strategy impacts and their parameters through a multi-objective optimization process, considering ease of implementation and result outcomes.

This research stems from two main issues found consistently throughout the literature study; the focus on energy consumption as a baseline for building sustainability and the implementation of optimization strategies for an already existing project, developing strategies for its improvement.

What is being done?

After the adoption of the Paris Agreement in 2015, aiming to curb global temperature rise below 2°C, there is a need for buildings to reduce energy consumption, becoming near zero energy buildings by 2050. Although energy simulations offer valuable data towards building adaptation to reduce energy consumption, they visualize the problem from purely an energy perspective, disregarding other factors influencing interior comfort.

Optimizations assist towards improving building operations by implementing energy reduction strategies such as volume and window geometry (Laouadi et al., 2002), material selection optimization (Vighnesh et al., 2021) or window area (Persson et al., 2006).

Energy Simulations

When running energy simulations, the setting is often an existing building. The simulations are run for the current (base) design and are compared to a series of optimization results based on a parametric model (improved design).

Possible improvement strategies are then presented to reduce energy consumption based on multiple trial and error simulations. Implementing the best performing simulated scenario will benefit the building operation and reduce energy consumption. However, major renovations such as changing window sizes, rotating a building or modifying walls are not always plausible or cost efficient.

Since the implementation of computer aided design optimization it has been possible to improve structural elements (Van Thai et al., 2022), façade design and paneling (Hinkle et al., 2022), orientation (Hakim et al., 2021), window characteristics (Persson et al., 2006), material selection (Vighnesh et al., 2021) and geometry (Granadeiro et al., 2013), amongst others. Despite the varied range in optimization possibilities towards an efficient building, the implementation of such a workflow does not reflect as effective when looking at new constructions.

A workflow considering various improvement parameters (multi-objective) towards interior comfort, which can be implemented at early design stages, will greatly reduce the need for renovations and future building adaptations whilst reducing energy consumption.

1.3. Research Questions

Main Research Question:

How can a multi-objective optimization workflow assist in early design stages towards a climate responsive design?

Sub-questions per field of research:

Climate Design

Subquestion 1

• What are the climate-responsive design strategies used per climate type?

Subquestion 2

• Which design principles support each other and what are the possible conflicts?

Subquestion 3

• How can the effects of climate change impact the design decisions based on current climatic conditions?

Design Informatics

Subquestion 4

• How does a multi-objective optimization workflow empower design development?

Subquestion 5

• How can simulation data be integrated into current & future workflows?

Subquestion 6

• What are the limitations from integrating an optimization workflow into a design process?

1.4. Design Objective

Design Assignment

The final outcome of this research will consist of a two-step approach. The first being a workflow proposal for a multi-objective optimization problem where user inputs will influence design decisions qualitatively while computational simulations provide a set of options, guiding the design through quantitative data. The workflow will be tested and adjusted to determine best overall results, gathering data from iterative analysis whilst modifying approximation possibilities.

The second section will focus on testing the workflow based on two criteria. The first criteria will focus on the results provided by the workflow itself with regards to building operation metrics such as solar heat gains, night-sky cooling, natural air cooling, energy performance and solar accessibility.

When considering workflow efficacy, it's necessary to verify the workflow's ease of use, knowledge requirements and time to output procedure.

Testing will therefore be quantitative and qualitative, culminating in a novel approach towards implementing data driven passive strategies into a climate-responsive design.

Research Workflow

The research develops over three phases where each phase's conclusions sequentially informs the next.

Phase 1: Research (Climate & Passive Strategies)

This phase focuses on gathering information on climate and its classifications. Research will focus on types of climate data available, their gathering method and climate classification from a data driven perspective.

In parallel, research into various types of passive design strategies will be conducted, pairing the strategies to each climate type based on their operating principles. The aim is to gather knowledge as to what passive principles operate the best under specific climatic conditions and determine when these climatic conditions are met by using the climate data obtained in the first research phase.

Coupling data with passive strategies will guide the decision making process throughout the workflow design phase by integrating the strategies based on conditional criterion.

Phase 2: Design (Workflow Development & Parametric Optimization)

This is the main section within this research project, addressing a proposed workflow to aid in the early design phase decision making process. The use of computers towards full design optimization is optimistic and unrealistic which is why, within this workflow, a user and computer interaction process will be presented; having both qualitative and quantitative data as design inputs. The workflow will be developed based on previously tested workflows discovered during the literature research; adapting the process for an early design stage focusing on three main passive strategy components: Surface to volume ratio, ventilation and skin materiality and their integration towards a climate-responsive design.

The second workflow aspect will be analyzing climate data through methods explored during Phase 1 and offering passive design strategy options based

on climate data analysis. As a whole, the process aims at offering key parameters during the initial design stages to create an efficient building based on climatic needs whilst providing a list of further design strategies which can be implemented.

Phase 3: Validation

The final phase focuses on testing the proposed workflow. Through an iterative process data will be generated for each climate type, combining a series of design priorities and needs from a multi-objective approach.. Data from the process will be compared to show the benefits and limitations of the proposed workflow.

The validation process does not only function as the final output, it becomes an integral part of the validation workflow, occurring at various stages through the workflow development for parameter adjustment and process modifications.

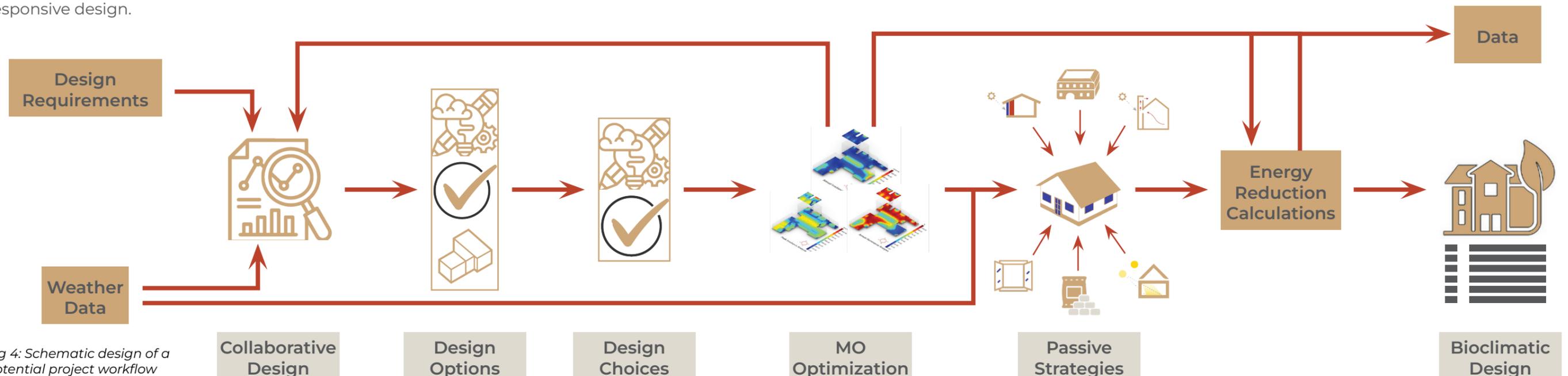


Fig 4: Schematic design of a potential project workflow

1.5. Project Scope

The present research will narrow the focus on three aspects, typology, multi-objective optimization strategies and climate responsive passive design strategies. The aim of narrowing the scope is to make the research feasible, researching at a smaller scale with the intention of scaling the process to other typologies and design strategies in the future.

Typology

Housing is chosen as a relatively stable typology, with variations by location and culture. However, the volume has smaller variations than any other typology and in many cases the program remains fairly consistent. Furthermore, results can be compared to Passivhaus standards since Passivhaus' database is open for consultation and building performance.

Optimization Strategies

Optimization strategies are chosen based on the impact potential, especially during an early design stage. Orientation, surface area to volume ratio, window to wall ratio and shading have a significant impact on daylight and energy performance (Musunuru, 2015). The integration of these strategies is best at the conceptual level, determining values that can influence performance such as building form, materials, glazing and shading (Stevanovic, 2013).

Climate-Responsive Design Strategies

Finally, six climate-responsive design strategies are chosen based on their common appearance in passive design strategies' review papers (Omran & Marsono, 2016 & Looman, 2017) and due to their potential use in various climate types, making them potential candidates towards reducing energy consumption regardless of project location.

Climate Representative Cities

Workflow generated building performance will be tested from various climate types: Tropical, Sub-Tropical, Temperate and Sub-Polar. However, to avoid testing results in each city and climate, representative cities are chosen (van Unen, 2019).

Tropical: Singapore

Sub-Tropical: Cairo

Temperate: Milan

Sub-Polar: Stockholm

Polar: Resolute

The proposed focus allows the development of a multi-objective optimization workflow at a reasonable scale, allowing for testing and adequate result and methodology evaluation.

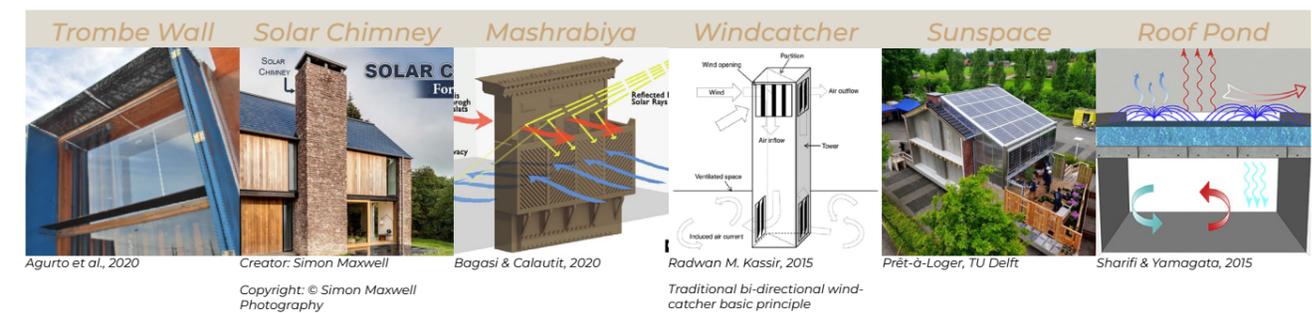
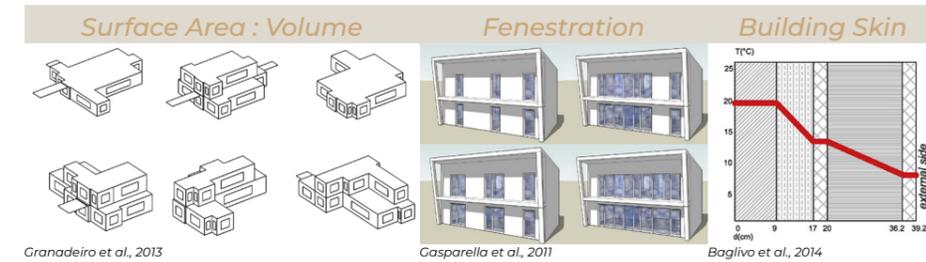


Fig 5: Project scope separate into 3 focus points: Typology, Optimization & Passive Strategies



Fig 6: Map of climate representative cities (van Unen, 2019) (Mansy, 2006)

2.1. Introduction to Climate Data

2.2. Climate Types & Categorization

2.3. Future Climate Predictions

2.4. Passive Design Strategies

2.1. Introduction to Climate Data

Information in a Weather File

Weather data gives access to information about a locations' climatic conditions, serving a manifold of industries throughout various sectors. It can also serve to detect climate change, evaluate climate models and simulate design iterations to deliver performance information. Weather data is derived from a compilation of climatic recordings over a period of 20 to 30 years (Herrera, 2017). The data is cleaned from anomalies and organized to define a 'typical' weather pattern in a given location. A typical weather file presents hourly data for dry-bulb temperature, dew point temperature, wind speed, wind direction, sky cover, atmospheric pressure, precipitation and solar radiation.

Weather File Types

Given the extensive information provided, weather data is used to define design characteristics for a given location. The wide availability of weather files makes the information accessible around the world. Although there are various file types, the most commonly used are the Test Reference Year (TRY) the Typical Meteorological Year (TMY) and the International Weather for Energy Calculations (IWEC) (McLeod, 2012). These file types gather a mean monthly data from long-term historic data and compile it into a standardized text based file.

There has been an attempt to standardize weather files for the many locations across the globe. These files are accessible to the public and are readily available for use in building simulations. However, the lack of standardization means there are certain discrepancies amongst file types, the information they contain and their calculation methods towards generating any lacking data. The National Renewable Energy Laboratory (NREL) described the data as "not suited for designing systems" as it fails to "meet worst-case conditions" (Marion, 1995).

Weather File Drawbacks

Although weather stations are present around the world, there are instances where climates are not represented by the nearest station. Terrain differences can have a significant impact on recordings at a weather station compared to the city or town it represents.

The impact by the heat island effect in cities is not fairly represented in climate data files, severely under calculating the required cooling loads. Scenarios such as extreme weather events are also poorly represented as the weather file offers information for a 'typical' year. Extreme weathers are by definition rare events but failure to consider such eventualities might lead to serious consequences and system failures.

Given weather data files are produced from historical data, there is no information on how climate change affects weather patterns. Knowing such constraints, climate data files continue to be used as the basis for climate analysis and bioclimatic design.

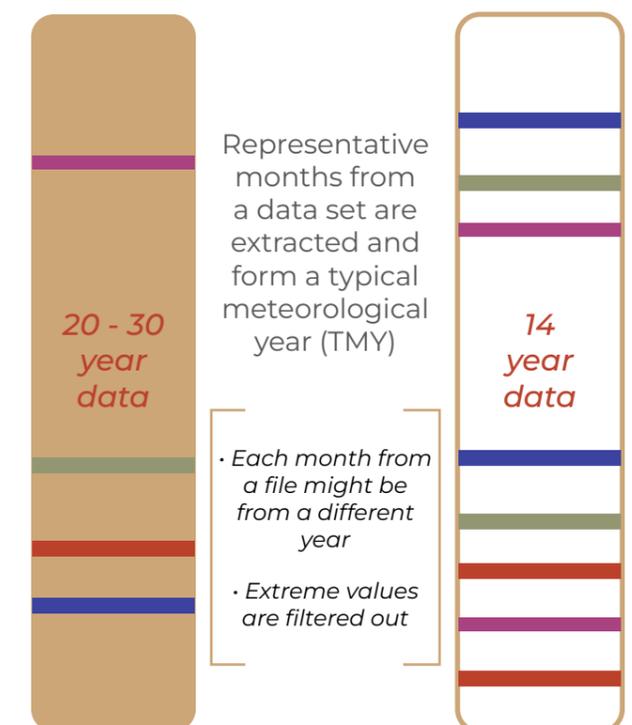


Fig 7: Schematic representation of a TMY file composition by selecting months in a 20 - 30 year period

Climate - Responsive

Climate responsive design links the local climate with building performance and operations. Its foundation lies on taking local weather patterns and using the information to develop an integrated design according to bio-climatic design principles such as: Orientation, surface area to volume ratio, ventilation requirements, materiality and solar gains. Climate responsive design aims to ensure interior comfort by using environmental resources to supply the space with sufficient heating and cooling.

Implementing passive design strategies allows buildings to interact with the environment, utilizing climatic cycles to draw, store or release heat, ventilate naturally when required and provide natural daylight. Passive design strategies operate on passive principles such as latent heat, evaporative cooling, radiative heat gains or pressure differences. Functionality of such principles is dependent on climatic conditions; daily cycles, through temperature differences between daytime and nighttime and seasonal cycles, differences and adaptive needs between summer and winter weather.



Fig 8: Map with passive strategy locations around the world

Weather and Design

Given the direct link between climate conditions and a buildings climatic design requirements, it is imperative to consider the information obtained from climate data during the early design stages to optimize orientation, massing, fenestration and shading (Musunuru, 2015).

Energy efficient designs vary from climate to climate; in cold climates compactness is more important than any other variable whilst in temperate climates the size of the openings and orientation are more important (Belmonte, 2021).

In hot and arid climates thermal insulation and increasing glass panes have shown to be the most effective whilst increasing infiltration does not favor the interior climatic conditions (Elhadad, 2019).

There are various studies supporting the implementation of passive strategies within different climate types, supporting the need to consider local climates and weather conditions towards a climate responsive design approach.

2.2. Climate Types & Categorization

Climate Data

Weather refers to the atmospheric conditions for a specific location at a specific time. Climate is a statistical description of weather over a sufficiently long period of time (Chen & Chen, 2013). Climate can therefore provide information about a locations weather changes, compiling past weather recordings and generalizing their cycles year after year. Climate data can serve to understand and prepare for certain climatic conditions, using historic information to take informed decisions.

Climate Classification Systems

Climate classification systems allow to easily identify and classify climate types and their yearly variability. Identifying climate types means simplifying all the information and data gathered in climate data files and categorizing world zones in relation to their historic climatic conditions. There are several climate classification systems, the most widely used are the Koppen-Geiger system (1954) and Thornthwaite (1948).

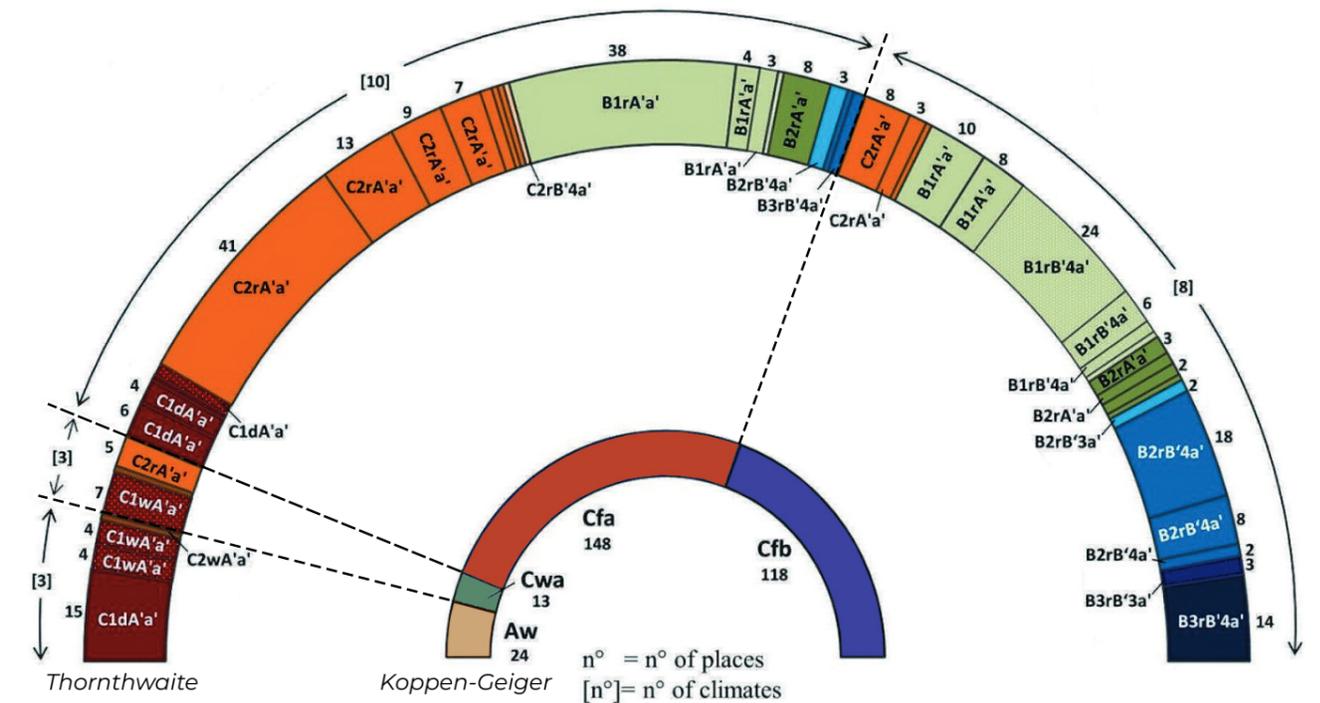


Fig 9: Climate classification comparison adapted from Aparecido et al. (2016) showing the distinct climate classifications from Thornthwaite and Koppen-Geiger

Koppen-Geiger

The Koppen-Geiger system relates air temperature and precipitation as the main factors affecting climatic conditions, linking these parameters to the presence and distributions of natural vegetation. The reasoning being, natural vegetation is a good indicator of regional climatic conditions.

The Koppen-Geiger classification system is based on 5 main classes ranging from A to E representing a Tropical, Arid, Temperate, Cold and Polar climate respectively and 30 sub-types that vary based on precipitation and temperature classes through different ranges across the 5 main classes.

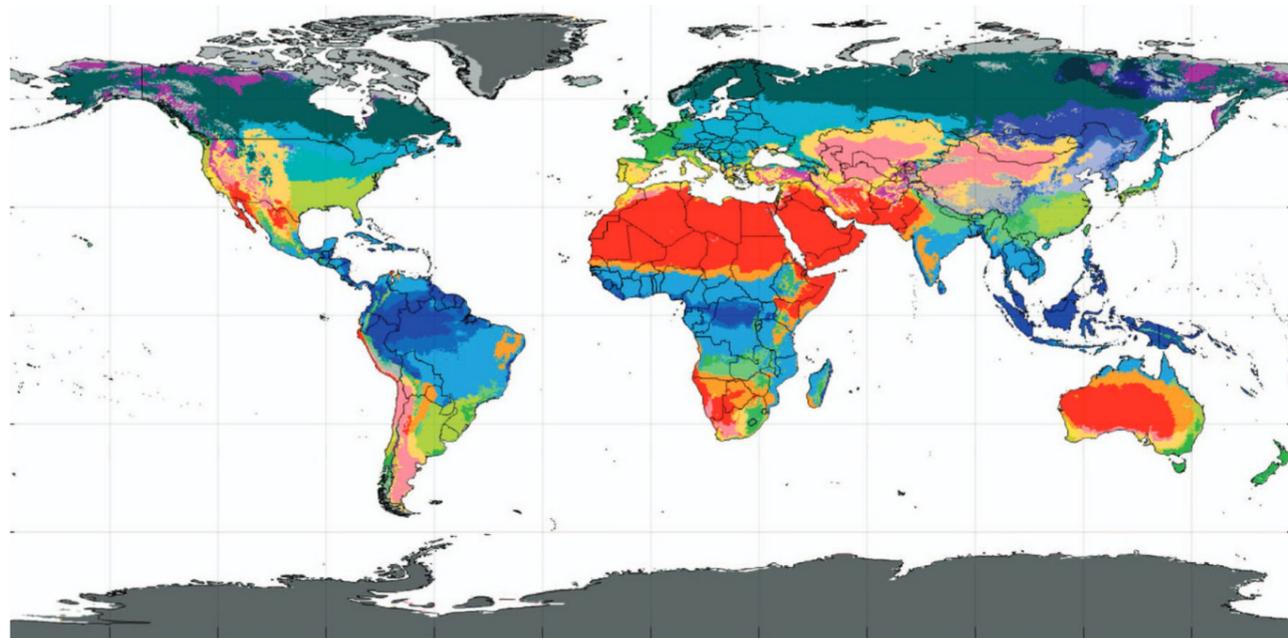


Fig 10: Koppen-Geiger climate classification from 1980-2016 climate data as referenced in Beck et al. (2018)

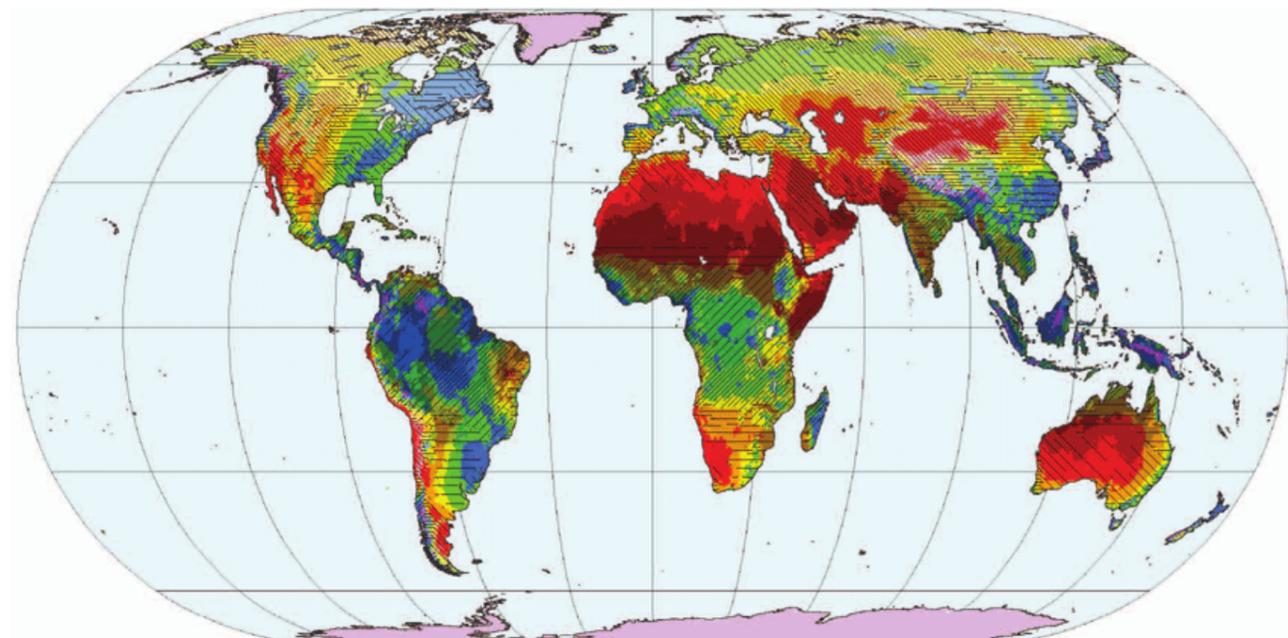


Fig 11: The revised Thornthwaite-type climate classification as cited in Feddema (2005)

Thornthwaite

Thornthwaite developed his climate classification system based on Koppen's original classification from 1918, considering air temperature and precipitation. However, Thornthwaite introduced formulas to account for potential evapotranspiration with elements of water balance, defining a climate as dry or humid relative to crop water needs. Such a classification leads to Thornthwaite's method having a greater array of possible climate types with a more complex classification, which not necessarily has an impact on the built environment as much as it has on crops.

Although Koppen-Geiger's classification offers a smaller range of climate classes, it is the most widely used, especially when defining climate types for the built environment.

Limitations of Using Current Climate Data

Using the Koppen-Geiger system as a reference for a location's climatic conditions is common practice within a building's climate studies due to its simple classification method. However,

the system does not provide a site's full weather patterns and how these might affect thermal comfort. In a weather file such as the typical meteorological year (TMY) or test reference year (TRY) there are factors such as wind speed, wind direction, sky cover, dew point temperature and atmospheric pressure which are not accounted for during Koppen-Geiger's classification. These factors affect thermal comfort, relating more to human perception than to a site's historical weather patterns.

Kottek (2006) published an updated version of Koppen-Geiger's climate classification map with data from 1951 to 2000, noting distinctive climate types per region than those previously provided by the Koppen-Geiger system. The impact of climate change has shifted the world's climatic conditions resulting in a decrease of Sub-Polar and Polar climates while increasing climate types A to C. Rubel & Kottek (2010) further developed a predicted mapping system for the years 2076 – 2100, considering various scenarios and the potential impact of greenhouse gas emissions over the years as a cumulative impact on the world's climatic conditions.

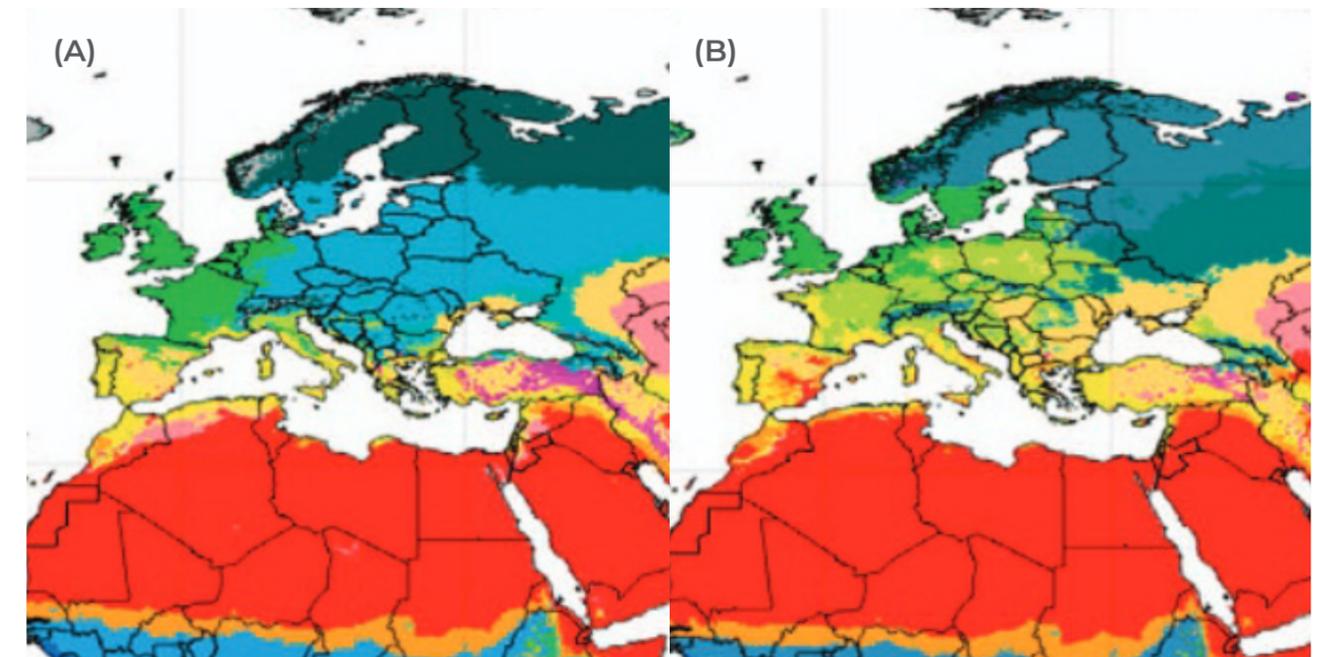


Fig 12: Comparison of a Koppen - Geiger classification from (A) 1980 - 2016 and (B) 2071 - 2100. Maps adapted from Beck et al. (2018)

Future Climate Scenarios

Energy simulations require local climate data to calculate consumption, forming a relationship between a project's passive and active strategies with its climatic context. In order to predict lifetime energy consumption, weather data files have to evolve to simulate future weather conditions (Troup, 2016). Morphing of climate data is used to forecast future events based on a range of possible outcomes and global emission scenarios. The Intergovernmental Panel on Climate Change (IPCC) offers 4 scenarios called Representative Concentration Pathways (RCPs) based on greenhouse gas emission possibilities.

When designing for a specific location there is a need to look into local climate and weather patterns to determine what the best design alternatives might be. Meteorological databases can be used to obtain historic weather data, gaining insight into a typical weather year. The biggest incongruence is the use of historic data towards a contemporary design. As presented by Kottek (2006) and later by Rubel & Kottek (2010) and Beck et al. (2018) there is an impact on the world's climatic conditions due to the rise of green house gases.

Weather patterns will begin to shift further towards the end of the century with a potential impact on a regional climate classification. Designing now, for a project with a lifespan of 60 – 80 years, using historic climate data as the starting point is a design discrepancy.

Representative Concentration Pathways

| | |
|----------------|---|
| RCP 2.6 | Stringent mitigation scenario |
| RCP 4.5 | Moderate scenario where stabilization occurs at radiative forcing of 4.5 W/m ² post 2100 |
| RCP 6.0 | Moderate scenario where stabilization occurs at radiative forcing of 6.0 W/m ² post 2100 |
| RCP 8.5 | Very high greenhouse gas emissions |

Emission Scenarios

Climate change causes dire impacts to our planets' weather and climatic conditions. The main cause is the generation of greenhouse gases that have been released into the atmosphere through years of civilizations' development. Greenhouse gas emissions will continue to be released into the atmosphere over the years impacted by social, economic and technological developments (IPCC, 2000).

In order to account for the accumulation of greenhouse gases and potential outcome models, the IPCC created various emission scenarios. Emission scenarios assess distinct pathways by looking at the social, economic and technological developments, culminating in various future possibilities based on emission trends.

Scenarios offer a possibility of how the future might unfold, serving to estimate the impact of climate change and assist in climate modeling, assessing the impacts and adaptation needs. The first set of scenarios generated by the IPCC in 1992 and later revised in 1996 consisted of 40 special report on emission scenarios (SRES) which cover a wide range of characteristics for future possibilities.

SRES Scenarios:

A1: Rapid economic growth with a mid-century population peak. Fast introduction of new and efficient technologies, increased cultural and social interactions and a reduction in per capita income differences.

A1FI: Fossil fuel intensive

A1T: Non-fossil energy sources

A1B: Balance across all sources

A2: Individualistic scenario, a self-reliance and preservation of local identities. Global population is on a constant increase and economic development is centered in specific locations.

B1: Population peaks mid-century, there is economic growth in the service and information industry. There is a reduction in material consumption and a use of clean and resource-efficient technologies. Equity improves but there are no climate initiatives.

B2: Environmental solutions are developed at a local scale, impacting economy, society and technology. Populations grows but at a slower rate.

Although SRES portray various potential outcomes regarding greenhouse gas emissions, they do not include any policies to reduce climate change or its mitigation. All SRES consider a 'business as usual' pathway with various degrees of characteristics shaping future climatic conditions.

Drivers of Green House Gas Emissions

- Population
- Economic activity
- Lifestyle
- Energy use
- Land use patterns
- Technology and
- Climate policy (Pachauri et al., 2015).

When current climate data values are taken; their values shifted, stretched or scaled, it is possible to reflect future climate projections (Belcher, Hacker and Powell, 2005).

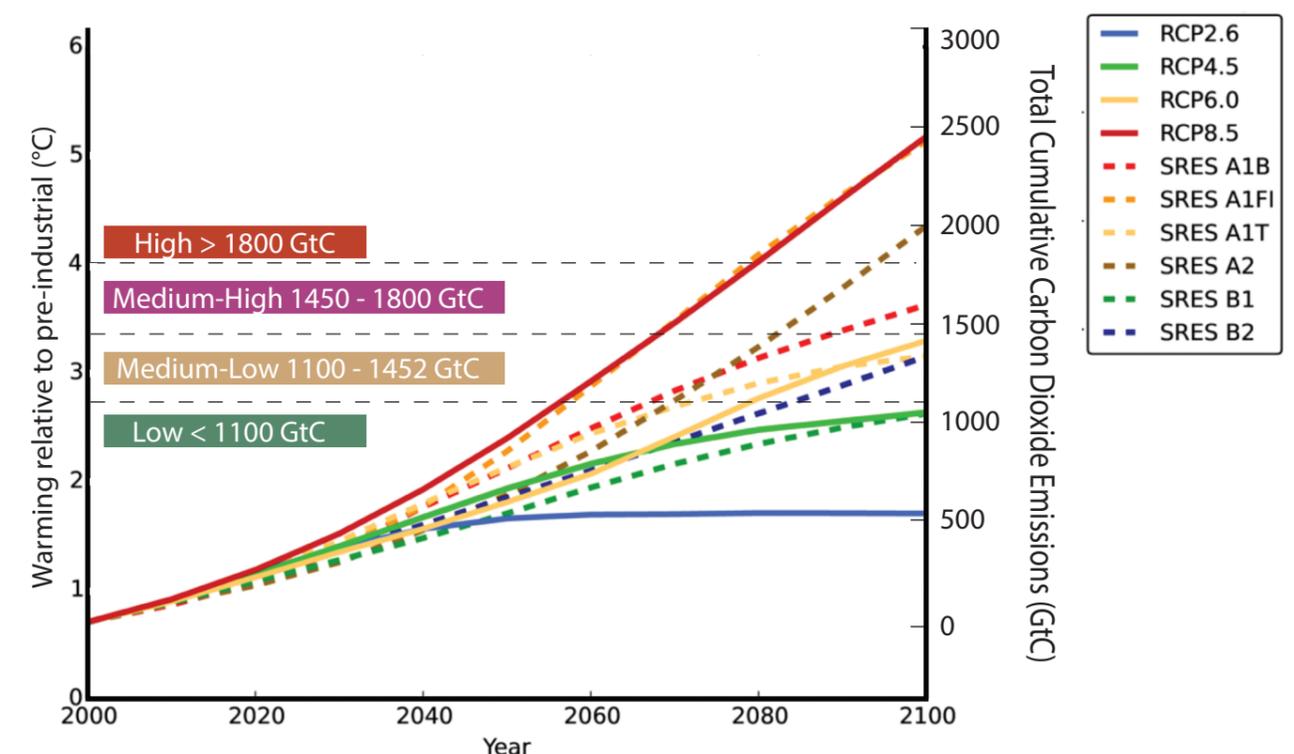


Fig 13: Comparison of RCPs and SRES and the predicted emissions in each scenario as seen in IPCC (2000)

Representative Concentration Pathways

Representative concentration pathways (RCPs) were developed during the IPCC's fifth assessment report (2014) as a new way of viewing long-term climate goals. RCPs are categorized by greenhouse gas concentrations resulting in total radiative forcing increasing by a specific amount by 2100. Radiative forcing is the exchange between incoming and outgoing radiation at the top of the atmosphere. Targets for 2100 have been set at 2.6, 4.5, 6.0 and 8.5 W/m², impacting global mean temperature increases differently.

Similar to SRES, RCPs are not policy recommendations nor finite predictions as they present a wide range of outcomes. RCPs are expressed as pathways, representing the ability to adjust and the possibility of achieving a result in more than one way. As such, climate policies can be developed and categorized accordingly, representing a potential pathway's process (Met Office, 2018).

Representative concentration pathways can influence and be influenced by policies. Specific pathways or decisions taken can impact CO₂-eq emissions, changing the path's trajectory. Mitigation and adaptation methods can be implemented towards reducing climate change. These efforts become more challenging as climate change increases, benefiting more from an early stage implementation (Pachauri, 2015).

2.3. Future Climate Predictions

There is a global consensus amongst the scientific community that climate change is having an impact on climate. Global CO₂ emissions will continue to have an impact on global weather patterns causing temperature to rise as greenhouse gases accumulate in the atmosphere. Rising temperatures will cause global climate types to shift and change over the next decade.

Building simulations are an important method to analyze a building's performance with the aim of reducing energy consumption. Weather data is required to simulate the buildings local environment and its performance within a defined context. Data obtained from simulations is then used to determine strategies to reduce lifetime energy use. Climatic context is important for a building; interacting with the built environment through sunlight for solar heat gains, wind for ventilation and temperature for building heat exchanges.

When designing and running energy simulations, data from historic weather files is used. This leads current climate-responsive and future designs to be out of date even before they are completed. Today's designs should withstand future changes in local climatic conditions, acknowledging climate change and adjusting weather files to represent future weather scenarios.

Prediction Methodology

There are two main methods to generate future climate scenarios, analogue and global circulation models (Belcher et al., 2005). The analogue scenario uses current weather information from a different location to that of the project's site but with a similar climate. This is not an ideal solution as climate data relies on latitude for specific climatic conditions such as solar radiation.

Global circulation models simulate atmospheric processes based on empirical calculations. In order to provide greater detail for a specific location, downscaling is required. Adjustments to current weather files through global circulation models offers weather forecast predictions. This process is called morphing as it combines calculations run for future global scale impacts and local climate data to determine future scenarios for a specific location.

Belcher et al. (2005) explored a morphing methodology for climate data, presenting a workflow and a calculation method to obtain future weather predictions based on global circulation models obtained from the UK Climate Impacts Programme (UKCIPO2) and calculating the effect these simulations have on present-day data obtained from the Chartered Institution of Building Service Engineers (CIBSE).

Research concluded it is possible to combine present-day data with climate model results; shifting and stretching data to represent constantly changing climatic conditions in order to obtain future weather patterns, whilst preserving realistic weather sequences and location.

Data Morphing

Data morphing provides site specific results towards simulating future conditions based on weather trends, accounting for variability in future weather and emission scenarios. By utilizing morphed climate data, it is possible to calculate a project's lifetime energy consumption (Troup, 2016) and therefore simulate a building thermal performance and comfort.

Although morphing considers global circulation models, which are calculated considering various planetary processes, it does not account for climate change as a morphing factor, since the effects of climate change are unknown. Although two data file types are required to calculate future scenarios, data morphing is a simple and flexible process applicable in any location with sufficient weather data.

Morphing data offers a plausible approximation towards future climatic conditions and, although calculations are empirical it is only one potential outcome from various scenarios.

Global warming will continue to present a threat to our planet, changing regional climatic conditions. Sub-tropical climates will expand whilst polar and temperate climates decrease in surface area (Chen & Chen, 2013).

Taking into consideration the constant change of the planets climatic conditions has a great potential within the design process. Although morphing data might not give a precise outcome, it can still serve as a safety factor towards future proof designs.

Integrating the morphing process within early design stages has the potential to shift design priorities to tackle future climatic conditions. There are three possible predicted outcomes:

1. Morphing does not show a significant change in current climate data



No effect

2. Morphing shows an impact in climatic conditions



Climate classification type changes and design strategies are adjusted

3. Morphing shows an impact in climatic conditions



Climate classification changes but design strategies work equally well in both climate types

Climate Morphing Tool

CCWorldWeatherGen is a tool developed by the Sustainable Energy Research Group from the University of Southampton and the Department of Mechanical Engineering from the University of Malaya in Kuala Lumpur. The tool is used to morph present-day weather data from an Energy Plus weather file (EPW) into a 2020, 2050 or 2080 weather file using the IPCCs A2 emission scenario. The five climate representative cities (Singapore, Cairo, Milan, Stockholm & Resolute) have been used to compare current and morphed weather data according to the Koppen-Geiger climate classification system.

In order to morph climate data, CCWorldWeatherGen uses nine climate variables (Chen & Chen, 2013) obtained from global circulation models:

1. Daily mean temperature (TEMP)
2. Maximum temperature (TMAX)
3. Minimum temperature (TMIN)
4. Horizontal solar irradiation (DSWF)
5. Total cloud cover (TCLW)
6. Total precipitation rate (PREC)
7. Relative humidity (RHUM)
8. Mean sea level pressure (MSLP)
9. Wind speed (WIND)

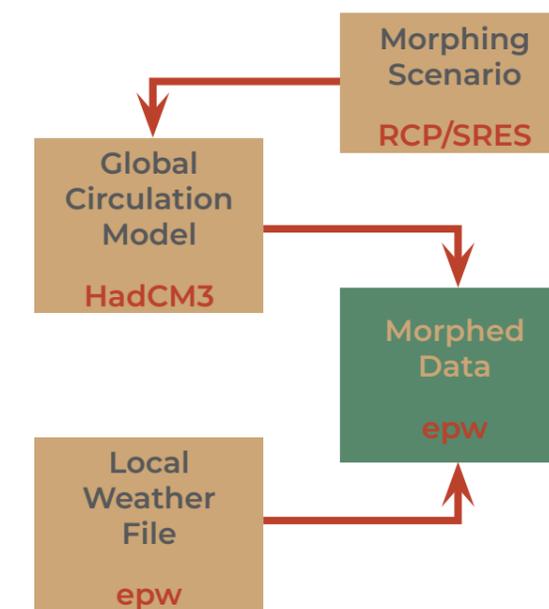


Fig 14: Schematic design for data morphing methodology

| VARIABLE | SYMBOL | UNITS |
|---------------------------------------|--------|------------------|
| Max. Temperature | TMAX | °C |
| Min. Temperature | TMIN | °C |
| Daily Mean Temperature | TEMP | °C |
| Total Precipitation Rate | PREC | mm/month |
| Snowfall Rate | SNOW | mm/month |
| 10 m Wind Speed | WIND | m/s |
| Relative Humidity | RHUM | % |
| Total Cloud in Longwave Radiation | TCLW | % |
| Net Surface Longwave Flux | NSLW | W/m ² |
| Net Surface Shortwave Flux | NSSW | W/m ² |
| Total Downward Surface Shortwave Flux | DSWF | W/m ² |
| Soil Moisture Content | SMOI | mm |
| Mean Sea Level Pressure | MSLP | hpa |
| Surface Latent Heat Flux | SLHF | W/m ² |
| Specific Humidity | SPHU | g/kg |

Table 1

Data collected in an HadCM3 file. Highlighted data is used for the morphing process.

Since global circulation models are all projected climate variables, the results might greatly vary depending on the circulation model used. HadCM3 is the global circulation model used within the CCWorldWeatherGen tool and has been widely used for the IPCCs Third, Fourth and Fifth Assessment (Met Office, 2018).

Coupling HadCM3 with an A2 scenario will provide results for an emission scenario considered as 'business as usual', where population growth occurs at major urban hubs and, although it is possible to obtain predictions for different time periods, the emission's scenario does not change.

Data from Table 1 and Table 2 are combined in formulas that shift, stretch or shift and stretch the data. Combining HadCM3 models with regional EPWs. Table 3 shows the results obtained for 6 climate representative cities for current and morphed weather data.

| VARIABLE | SYMBOL | UNITS |
|---|--------|----------------------|
| Global Solar Irradiation on Horizontal | gsr | W/h · m ² |
| Diffuse Solar Irradiation on Horizontal | dsr | W/h · m ² |
| Sunshine Duration: Radiation Site | sf_r | hour |
| Sunshine Duration: Synoptic Site | sf_s | hour |
| Cloud Cover | cc | oktas |
| Dry-bulb Temperature | dbt | °C |
| Wet-bulb Temperature | wbt | °C |
| Atmospheric Pressure | atpr | mbar |
| Wind Speed | ws | m/s |
| Wind Direction | wd | degrees |
| Rain Amount | rs | mm |
| Rain Duration | rd | hour |
| Solar Altitude: Degrees from Horizontal | solalt | degrees |

Table 2

Data collected in an epw file over a period of 20 - 30 years. All present data is morphed based on a chosen scenario.

| Sheet Name | City | Data Date | Latitude | Mean Annual Precipitation (MAP) | Summer Precipitation | Mean Annual Air Temperature (MAT) | Pthreshold | Tcold | Pdry | Thot | Psdry | Pwdry | Pswet | Pwwet | Tmonth | Climate Classification |
|----------------|------------------------|-----------|----------|---------------------------------|----------------------|-----------------------------------|------------|--------|-----------------|-------|-----------------|-----------------|-----------------|-----------------|--------|------------------------|
| | | | N | mm ² | mm | °C | °C | °C | mm ² | °C | mm ² | mm ² | mm ² | mm ² | | |
| Singapore | Changi.Intl.AP | 2013 | 1.37 | 2366.70 | 1172.20 | 27.86 | 69.72 | 26.91 | 101.96 | 28.59 | 109.53 | 101.96 | 119.42 | 115.03 | 12 | Af |
| Singapore.2080 | Changi.Intl.AP | 2080 | 1.37 | 2113.27 | 1038.18 | 31.23 | 76.46 | 30.09 | 85.82 | 32.19 | 99.68 | 85.82 | 100.00 | 100.00 | 12 | Af |
| Cairo | Cairo.Intl.AP | 2016 | 30.12 | 14.40 | 1.10 | 22.13 | 44.26 | 13.59 | 17.25 | 28.72 | 26.38 | 17.25 | 68.07 | 39.82 | 12 | BWh |
| Cairo.2080 | Cairo.Intl.AP | 2080 | 30.12 | 10.49 | 0.91 | 26.11 | 52.21 | 17.07 | 10.44 | 34.06 | 16.01 | 10.44 | 71.98 | 39.84 | 12 | BWh |
| Milan | Milano-Bergamo.Intl.AP | 2016 | 45.67 | 1197.40 | 690.20 | 14.04 | 42.09 | 3.47 | 9.69 | 24.29 | 22.23 | 9.69 | 47.00 | 24.89 | 7 | Cfa |
| Milan.2080 | Milano-Bergamo.Intl.AP | 2080 | 45.67 | 1105.98 | 514.57 | 18.78 | 51.55 | 7.53 | 11.80 | 31.94 | 20.37 | 11.80 | 31.81 | 23.13 | 9 | Cfa |
| FiSmith | Fort.Smith.CS | 2012 | 60.03 | 343.40 | 226.00 | -0.76 | 12.49 | -20.40 | 1.40 | 17.76 | 5.93 | 1.40 | 27.40 | 8.40 | 4 | Dwb |
| FiSmith.2080 | Fort.Smith.CS | 2080 | 60.03 | 392.44 | 252.19 | 3.62 | 21.25 | -15.65 | 1.76 | 23.24 | 7.06 | 1.76 | 33.59 | 9.57 | 5 | Dwa |
| Stockholm | Stockholm | 2009 | 59.35 | 606.80 | 353.90 | 8.18 | 30.36 | -1.10 | 8.14 | 18.61 | 10.05 | 8.14 | 33.56 | 17.11 | 5 | Dfb |
| Stockholm.2080 | Stockholm | 2080 | 59.35 | 662.51 | 373.77 | 13.08 | 40.16 | 2.97 | 8.73 | 25.00 | 12.25 | 8.73 | 31.69 | 19.31 | 7 | Cfa |
| Resolute | Resolute | 1967 | 74.72 | 143.77 | 105.03 | -16.53 | -5.05 | -32.15 | 3.00 | 3.67 | 6.00 | 3.00 | 28.00 | 15.00 | 0 | ET |

Table 3

Climate classification for current and morphed weather data for climate representative cities.

2.4. Passive Design Strategies

Design's Relationship to Climate

Designs which respond to climate (climate-responsive) serve as the intermediary between the indoor and the outdoor environment (Hastings, 1989). Climate responsive design defines the building as an environmental filter, excluding unwanted forces and admitting beneficial ones. As such, the design is in tune with natural dynamics and systems leading to thermal comfort without the requirement of extra energy consumption.

On the other end of the spectrum is a climate-insensitive design where there is no interaction with the environment at all. Building operations ignore local climate and are not affected by exterior forces, providing all necessary needs mechanically (Looman, 2017).

Between a climate-responsive and a climate-insensitive design interaction is a climate-combative design. Climate combative designs take into account local climate as a means of defining a building's insulation requirements towards maintaining thermal comfort (Looman, 2017) without the need of excess energy; but fail to understand and integrate into local climatic systems.

Climate-responsive designs are strongly connected to the exterior environment, giving users the flexibility to interact and adjust their climatic needs to satisfy their comfort levels; for example, through opening or closing a window, shutters or curtains. Such options are seldom possible in a climate-insensitive design as opening a window will cause exterior and interior air temperatures to mix, impacting the systems' efficacy and creating discomfort zones within the built envelope.

Climate-insensitive and climate-combative designs operate on a premise of improving thermal comfort, regardless of context based environmental factors, maintaining a steady temperature year round. On the other hand, climate-responsive design is highly dependent on local systems and climate conditions which at some

point might or might not be present. This would lead to some periods of thermal discomfort, either through the excess or lack of solar energy, winds or humidity. Studies have shown there are health benefits to mild cold exposures as our bodies adapt to these circumstances as it keeps our peripheral vascular system in motion (Van Marken Lichtenbelt et al. 2014).

Insensitive



Climate nor site is considered. All solutions are solved through active systems making the interior environment artificial

Combative



Climate is only seen as an achievable metric. Thermal comfort is only solved through high insulation levels

Responsive



Climate is part of the space's functionality. Weather cycles are considered within the building's operation to maintain thermal comfort

Analogue Climate

As a means of reducing the impact on climate change by reducing greenhouse gas emissions it is necessary to consider sustainable construction methods. Vernacular architecture focused on climate conditions to develop design principles, responding to the local climatic patterns and considering site over technology.

Vernacular architecture is architecture from the site, the local context it inhabits. It's characterized by using traditional materials from local or regional resources, making due with what is readily accessible. Such architecture styles encouraged the use of low tech systems used in smart ways to build comfortable spaces according to local climate and regional needs.

Passive design strategies are strategies which utilize climatic energy sources to provide thermal comfort without the use of electricity or the burning of fossil fuels. Passive strategies integrate into the natural system considering day and night, the passage of time and the movement of the wind and sun as a means to harness environmental energy cycles and local environmental flows.

Designs developed over the years with the knowledge of local climatic patterns serving as inspiration impacting orientations, room use patterns, ventilation

needs, sizing and the use of local materials. When needed, specific strategies were implemented in order to satisfy comfort levels which considered climatic patterns or cycles as an important source of energy.

Passive strategies do not require energy, operating based on site. User input is infrequently required for their use which makes them hard to control. Predictable weather patterns are needed for passive strategies to perform according to their designed intent, which is not always the case. Thermal comfort can therefore be impacted if weather events do not occur.

For example, if a trombe wall is used as a heat source it depends on sunlight to store thermal energy. If there is no sunlight the wall does not function according to its full potential. Similarly, if a wind catcher is to function accordingly, it requires wind to be present. If there is no wind, there is no natural ventilation. The dependence on external factors affects passive system reliability.

Climate Impact on Design

Passive strategies developed as a means to achieve thermal comfort without the use of electricity towards heating or cooling. Each strategy developed based on local climate patterns and user needs. Temperature and humidity determine what type of strategy will perform best under specific climate conditions considering: Average temperatures, temperature gradients, seasonal changes and how these temperatures affect humidity levels.

Numerous studies have shown reduced energy consumptions when implementing passive strategies within a design. Optimizing roof and wall insulation, glazing type, window to wall ratio and shading devices can reduce annual energy consumption by over 50% in humid subtropical climate (Gong et al., 2019). Similar parameters have shown to improve thermal comfort levels whilst reducing heating and cooling demands in a hot desert climate (Elhadad, 2019). Shading devices, natural ventilation and thermal insulations have shown to be important factors towards reducing energy

consumption in temperate climates (Mushtaha et al., 2021).

For existing residential units there is a potential of almost a 50% reduction in energy consumption when passive strategies are implemented during refurbishment (Chang et al., 2022). Many of the studies' simulation and optimization methods focus on analyzing existing housing units and improving their strategies, constantly showing an improvement in energy reduction and maintained thermal comfort.

Each climate zone has its own requirements and will perform better under specific circumstances. Vernacular architecture embraces local climate conditions as a means of reducing energy needs whilst maintaining thermal comfort. Designs have developed over time, influenced by traditions and culture from local builders who, through a trial and error process, have produced site-specific buildings (Zhigiang, 2010).

This is why igloos are built in polar regions or mud buildings are built in hot and dry climates. Each design choice has an

impact on how a building operates and its thermal comfort. This is also the reason why glass buildings are not usually built in hot climates as the building will incur too much solar radiation which would then need to be ventilated to reduce interior temperatures. Such design decisions are usually compensated by introducing active systems within a building such as air conditioning units for hot climates and heaters for cold climates.

To counter the need for active systems, passive design strategies can be used to improve thermal comfort. These strategies have to be integrated into the building's design for them to function correctly. Integrating passive strategies at an early stage shows greater potential and is done so at a lower cost (Evans, 2007).

Implementing passive strategies differs per climate type. Some passive strategies are used for heating and others for cooling but in general they all serve to improve the perception of thermal comfort. Based on the literature study, six passive design strategies are chosen based on their potential to function in more than one climate type with specific modifications.

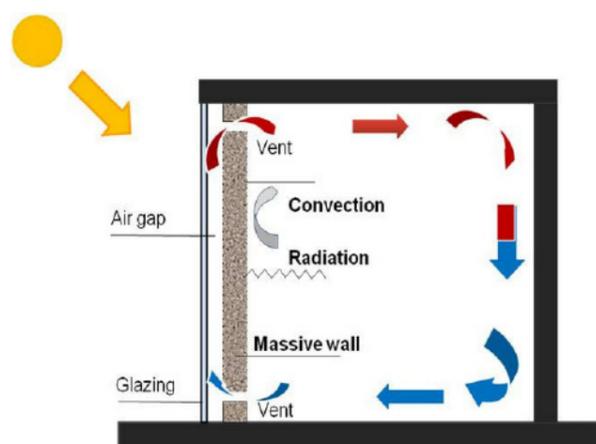


Fig 15: Working principle of a traditional Trombe wall and energy gain (Kartal & Özbalta, 2010)

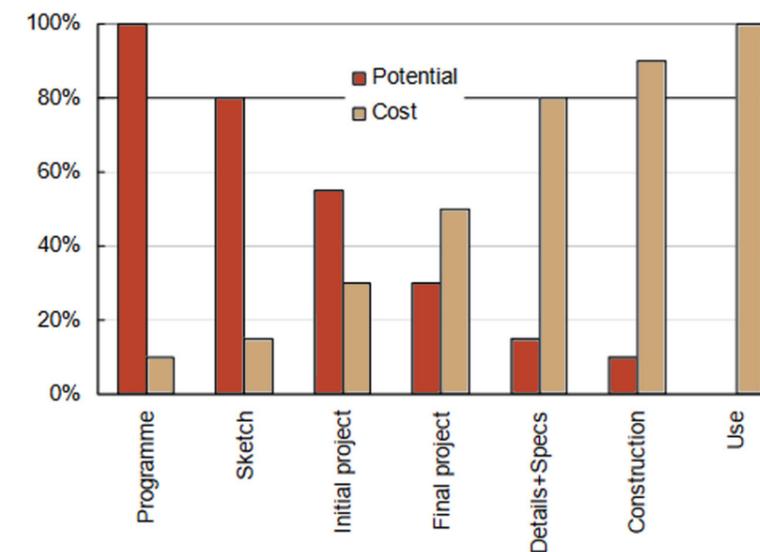


Fig 16: Design strategy implementation comparison amongst various design stages (Evans, J.M. 2007)

The intent is to provide a list of potential strategies which can be integrated into the design based on local climate data obtained from EPW files.

The passive design strategies chosen are:

- Wind catchers
- Sunspace
- Trombe wall
- Roof Pond
- Solar Chimney
- Shading Strategies

Although these can be used per climate type, under a Koppen-Geiger classification system, not all can be implemented in every location. Windcatchers for example require minimum wind speeds.

Not all passive design strategies will perform the same in every location but by providing climate based design options there is a greater potential towards energy reduction.

| Climate Type | Wind Catcher Type | Reference Papers |
|--------------|---|-------------------------------------|
| A | Depends on wind speed: • If wind speed > 3m/s use uni-directional • If wind speed < 3m/s use multi-directional • 9m high wind catcher performs best | Ghadiri, 2011 |
| B | Depends on wind speed: • If wind speed > 3m/s use uni-directional • If wind speed < 3m/s use multi-directional • 9m high wind catcher performs best • Use evaporative cooling strategies | Ghadiri, 2011 Zhang et al., 2021 |
| C | Depends on wind speed and cooling period: • If wind speed during summer > 3m/s use uni-directional • If wind speed during winter > 3m/s use multi-directional • If wind speed during summer < 3m/s use multi-directional • If wind speed during winter < 3m/s use uni-directional • 9m high wind catcher performs best | Ghadiri, 2011 |
| D | Not Applicable | |
| E | Not Applicable | |

Table 4

Wind catcher considerations per climate type and their reference papers

2.4.1. Wind catchers

Wind catchers have been proven to be effective in various climatic regions with different wind conditions. Hot and dry climate of Iran, hot and humid climate of the UAE and in the dry and mild hot weather of Afghanistan (Chohan & Awad, 2022), wind catchers have the potential to lower interior temperatures and improve thermal comfort.

A wind catchers' performance greatly depends on climatic conditions such as wind speed and wind direction. Performance conditions can be improved by increasing wind catcher height and modifying the number of openings. A manifold of design configurations allows wind catchers to function according to climate and site such as its plan design and the number of openings. Wind catchers perform best with winds over 3 m/s with a scoop or a bi-directional configuration. If wind speeds fall below 3 m/s a multi-directional wind catcher will perform best as it can serve to drag the air out from the building (Ghadiri, 2011).

Design versatility makes wind catchers an efficient and adaptable passive design choice towards cooling. Uni-directional wind catchers perform best when positioned at the corner of the room whilst multi-directional will perform best in the middle of a room. Performance can be enhanced by integrating evaporative cooling strategies to lower incoming air temperatures (Zhang et al., 2021).

The appeal for wind catcher's use has dwindled since the integration of HVAC systems, especially for peak summer conditions. In urban development's obstructions pose a further risk to a wind catcher's ability to capture air flows.

Wind catchers perform best in single-family homes which are usually located in suburban or rural settings. The integration of wind catchers might not provide the full ventilation rate required but will help in reducing peak loads. Design configurations make wind catchers an effective strategy for energy reduction. Wind catchers shall not act alone but in a combination with other strategies, aiming to improve thermal comfort whilst being conscious about energy consumption.

2.4.2. Sunspace

A sunspace is an addition to the main building with a glass façade acting as a thermal buffer between the exterior and interior. During winter it allows solar radiation to permeate and heat the opaque walls which separate the living space from the sunspace. During the day, these walls store thermal energy which is released into the sunspace during the night. Walls with thermal mass and a larger specific heat capacity will improve heat retention (Oliveti et al., 2012). Since heat is being released into a contained space the temperature in the main building will remain more stable when compared to a scenario without a sunspace.

Sunspaces are ideal passive solutions for cold regions, allowing the retention of solar radiation for longer, heating the space or avoiding temperature gradients. Oliveti et al. (2012) concluded the best positioning for a sunspace is the South façade due to higher solar incidence allowing for greater absorption coefficient for the main building's opaque wall.

| Climate Type | Sunspace Type | Reference Papers |
|--------------|--|--|
| A | Not Applicable | |
| B | • Use of single-glazed windows for a faster temperature change • Sunspace embedded in volume (one glass facade + roof) • Flat roof, same height as adjacent room • Width 45% of building's width • South facade • Use internal shading during summer periods to avoid overheating | Aelenei, 2014 Oliveti, 2012 Bataineh & Fayed, 2011 |
| C | • If $T_{hot} > \text{or} = \text{to } 22^{\circ}\text{C}$ use single-glazed windows, if not, use double glazed • Sunspace embedded in volume (one glass facade + roof) or along the full width of the longest south facing wall • Tilted roof, same height as adjacent room • Width 45% of building's width if embedded • South facade • Use internal shading during summer periods to avoid overheating | Aelenei, 2014 Oliveti, 2012 Bataineh & Fayed, 2011 |
| D | • Double glazed window to act as a buffer between sunspace and living space • Full width of the longest south facing wall • Tilted roof, same height as adjacent room • South facade • Use internal shading to avoid heat losses over night | Aelenei, 2014 Oliveti, 2012 Bataineh & Fayed, 2011 |
| E | • Double glazed window to act as a buffer between sunspace and living space • Full width of the longest south facing wall • Tilted roof, same height as adjacent room • South facade • Use internal shading to avoid heat losses over night | Aelenei, 2014 Oliveti, 2012 Bataineh & Fayed, 2011 |

Table 5

Sunspace considerations per climate type and their reference papers

A sunspace will function well under winter conditions but can cause problems during warmer months. Night ventilation and internal shading device improve the sunspace's thermal behavior in Amman's (Jordan) subtropical steppe climate (Bataineh & Fayed, 2011). A single glass pane will perform better for both winter and summer scenarios as the sun space will be allowed to heat up and cool down faster when compared to double-glass panes. Shading and ventilation techniques allow using the sunspace year round (Oliveti et al., 2012) in a hot summer Mediterranean climate in Italy.

Sunspaces are therefore a passive design strategy which can be implemented in both cold and warm climates with large temperature gradients between day and night. It is necessary to consider ventilation and shading strategies in order to reduce heat accumulation during summer. Internal shading will further assist during winter months, increasing the thermal resistance between the sunspace and the exterior climate, therefore avoiding heat losses over winter (Bataineh & Fayed, 2011).

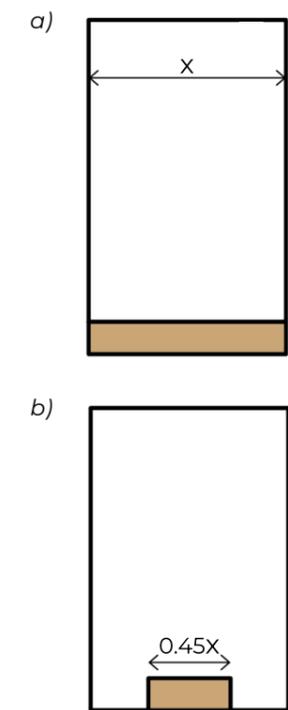


Fig 17: Floor plan view for two types of sunspace design based on Aelenei, 2014
a) Full length sunspace
b) Embedded sunspace

2.4.3. Trombe Wall

Trombe walls are highly reliant on solar gains, consisting of a thermal mass wall and a translucent surface through which sunlight can pass and heat the wall and thus the cavity between the interior and exterior space. Heat is transported into the living space through convection from the cavity due to the buoyancy effect (van Unen, 2019) and through radiation once the room temperature drops below the walls' temperature. Trombe walls therefore function the best in places where temperature differences between daytime and nighttime have a greater difference, reducing both heating and cooling demand (Corduban et al., 2020).

The cavity between the glass and the mass wall retains hot air, directing it into the living space or out through

a ventilation shaft, due to pressure differences. This double function makes it possible to integrate trombe walls in a variety of climate types. Agurto et al. (2020) determined trombe walls function well in coastal and in-land cities in the warm and temperate climate of Chile. Showing both summer and winter seasons demonstrate a reduction in energy consumption. Conduction is responsible for thermal energy release during low temperature periods (morning and afternoons) and convection delivers warm air during peak solar periods (usually midday) in a hot desert climate (Rabani et al., 2017).

Integration of a trombe wall can save around 20% in heating energy consumption for a house in a humid subtropical climate of France (Bojic et al., 2014). In a dry-summer subtropical

climate of Tunisia the annual heating consumption can be reduced by over 50% (Abbassi et al., 2014). Trombe walls have also been implemented in continental climates of Tibet, concluding the strategy is cost-effective for residential units whilst reducing energy consumption and greenhouse gas emissions (Zhang et al., 2020).

Trombe walls have been widely tested and implemented in various climate types as they serve heating and cooling scenarios, increasing the energy output of solar heat gains throughout the year. Their implementation is cost effective with a payback period of under one and a half years (Rabani et al., 2017). Their integration into single family homes with little obstruction from solar gains makes this strategy efficient, reliable and cost effective making it suitable for both warm and cold climate types as a means of reducing energy consumption and the generation of CO2 emissions.

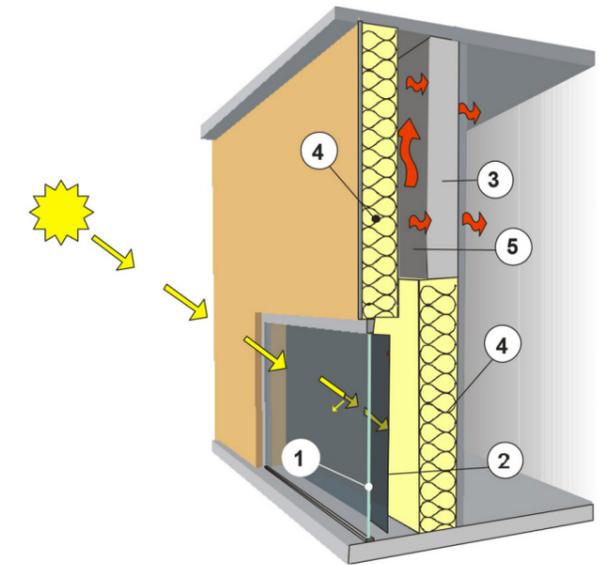
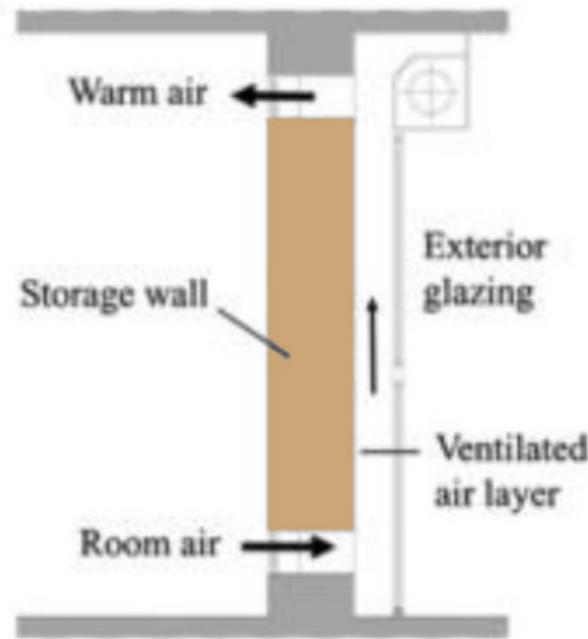


Fig 19: Diagram of a Trombe Wall suitable for sub polar and polar climates by Szyszka et al., 2022
 1) Triple glazing glass
 2) Black absorbing surface
 3) Thermal mass wall 12cm
 4) 0.038 W/m²·K insulation
 5) Air gap 15cm

Winter



Summer

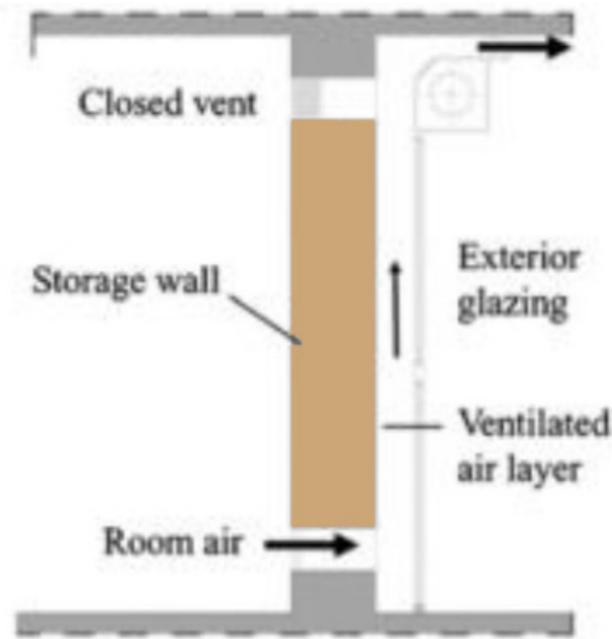


Fig 18: Section view of a Trombe Wall with ventilation gap, adequate for both summer and winter situations adapted from van Unen, 2019 cross referenced to Stazi, Mastrucci, & di Perna, 2011

| Climate Type | Trombe Wall Type | Reference Papers |
|--------------|---|---|
| A | Not Applicable | |
| B | <ul style="list-style-type: none"> Air gap of 300mm Trombe wall height same as adjacent wall Width = 37% of South facade length Window shading coefficient 0.9 Wall thermal conductivity 1.75W/m²·°C Specific heat capacity > 1900kJ/m²·°C Wall thickness 300mm Single glazing | Jaber, 2011 Rabani et al., 2017 Abbassi et al., 2014 |
| C | <ul style="list-style-type: none"> Air gap of 200mm Trombe wall height same as adjacent wall Width = 37% of South facade length Window shading coefficient 0.9 Wall thermal conductivity 1.75W/m²·°C Specific heat capacity > 1900kJ/m²·°C Wall thickness 300mm Single glazing | Jaber, 2011 Rabani et al., 2017 Abbassi et al., 2014 Agurto et al., 2020 |
| D | <ul style="list-style-type: none"> Air gap of 150mm Trombe wall height same as adjacent wall Width = 37% of South facade length Window shading coefficient 0.9 Wall thermal conductivity 1.75W/m²·°C Specific heat capacity > 1900kJ/m²·°C Wall thickness 200mm Single glazing 4mm | Jaber, 2011 Rabani et al., 2017 Abbassi et al., 2014 Bajc et al., 2015 |
| E | <ul style="list-style-type: none"> Use of Thermo-Diode Trombe Wall Triple glazing glass Window shading coefficient 0.9 g value 0.58 0.038 W/m²·K insulation 120mm mass wall above insulation South facade Height same as adjacent room Width 900mm per south room | Szyszka et al., 2022 |

Table 6

Trombe wall considerations per climate type and their reference papers

2.4.4. Roof Pond

Roof ponds are a varied and versatile passive strategy, serving a wide range of climate types based on their design adaptations. Sharifi and Yamagata (2015) reviewed 19 different roof pond variants across 17 different countries to determine strategies based on climate type. Roof ponds work best in arid climates but their integration in humid climates is possible if evaporation is prevented. Evaporative cooling has an operational limit at 50% relative humidity, between 50% - 70% relative humidity operation is reduced and above 70% relative humidity evaporative cooling becomes useless (Kharrufa & Adil, 2008). Furthermore, roof ponds can also be integrated in freezing conditions but only if a non-convective zone is integrated by combining water with viscosity additives (Sharifi & Yamagata, 2015).

Roof ponds are mainly used for cooling during hot summer periods, being able to reduce the interior's average temperature by acting as thermal mass and by

improving night-time ventilation through evaporative cooling (Hassan & Beliveau, 2007). By utilizing all three energy transfer principles (radiation, convection and conduction) interior temperature gradients are eliminated (Kharrufa & Adil, 2008), maintaining thermal comfort throughout the day. Indirect evaporative cooling assists with heat dissipation, radiant cooling takes advantage of the temperature differences between water and air to lose energy and, a heat exchange is mitigated between interior and exterior by using the water's thermal mass (Suarez et al., 2018).

Heating a space is possible during cold periods by using the roof pond to capture solar energy throughout the day (heating the water) and covering it during the night with an insulated roof panel. Energy is then radiated to the interior or at least reduces the temperature gradient between interior and exterior, reducing the rate of heat loss.

| Climate Type | Roof Pond Type | Reference Papers |
|--------------|--|--|
| A | <ul style="list-style-type: none"> • Skytherm, shaded with closed waterbags and ventilated roof pond work in humid climates (cool-roof uses water spray system) • 120mm of water for faster temperature changes • Skytherm thermal resistance 2.822 m²K/W • Closed during the day and opened at night for night cooling • Area spanning complete roof area | Sharifi & Yamagata, 2015 Kharrufa & Adil, 2008 |
| B | <ul style="list-style-type: none"> • Open roof pond without sprays • Roof pond with movable insulation • 30–40 mm Water • 300–900 mm Ventilated air layer • 0.2 mm Polyethylene foil • 200–300 mm Ventilated air layer • 10 mm Polystyrene sheet • 0.8 mm White Galvanized steel sheet | Sharifi & Yamagata, 2015 Kharrufa & Adil, 2008 Gonzalez, 2015 |
| C | <ul style="list-style-type: none"> • Use of open pond without sprays • Roof pond with cover during colder months to have extra insulation layer on the roof • Roof thickness 30cm • 9–16 mm Water • Expanded polystyrene insulation 6 cm • Use of windbreakers to reduce water cooling through convection | Sharifi & Yamagata, 2015 Hassan & Beliveau, 2007 Suarez et al., 2018 |
| D | Not Applicable | |
| E | Not Applicable | |

*Text in red is assumed based on recurring literature findings

Table 7

Roof Pond considerations per climate type and their reference papers

Different design strategies for roof ponds allow these to be integrated in different climate types from A to C from the Koppen-Geiger climate classification system. Table 7 shows the recommended roof-pond design type for each climate classification type based on Sharifi and Yamagata's (2015) research. This paper focuses on passive strategies so any roof ponds with mechanical supports are excluded. Priority is further given to strategies with low maintenance costs and ones which do not require water sprays as these have limited use in water strained locations.

Although roof ponds show great potential towards reducing heating and cooling energy requirements, even when showing greater performance against other passive strategies (Sharifi & Yamagata, 2015), it is important to consider their operation alone cannot account for roof ponds to be the only passive strategy (Suarez et al., 2018). A combination of passive design strategies is therefore recommended as a means of maintaining a livable space under comfort levels and reducing the energy consumed for heating and cooling throughout the year.

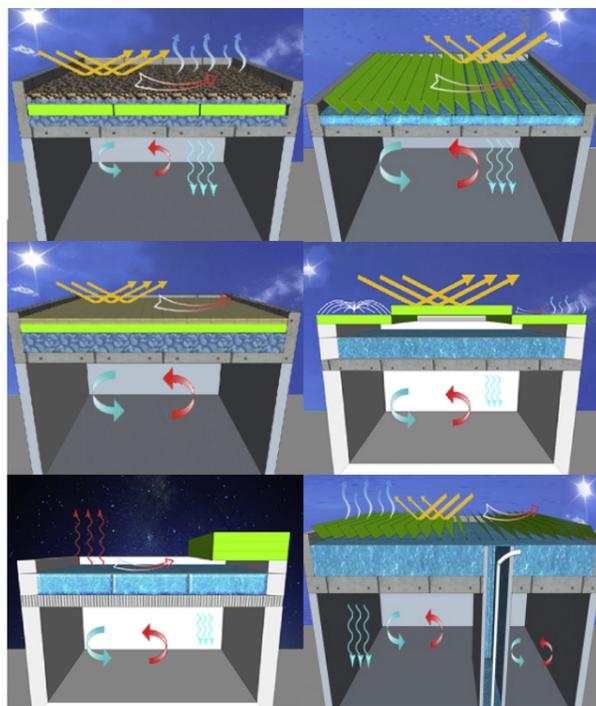


Fig 20: Roof Pond variant compilation gathered from Sharifi & Yamagata, 2015

2.4.5. Solar Chimney

Solar assisted natural ventilation strategies help to cool interior spaces by utilizing the sun's energy to heat the air and create pressure differences, forcing the air inside to exit the room, exchanging interior warm air with fresh air from the outside. Solar chimneys allow such operations by having a translucent wall. When sunlight hits the glass, air in the gap is heated, density decreases and the buoyancy effect causes air to move upwards (Salari et al., 2020). Solar chimneys therefore operate best in warmer climates (Afonso & Oliveira, 2000). Such a dependence on the sun for ventilation purposes means solar chimneys are unproductive during the night or days without sun (Salari et al., 2020).

Several studies have been carried out to determine a solar chimneys size, height, material use and angle for optimal performance. These studies have varied climate types, all focusing on solar chimneys for cooling purposes. Chen et al. (2003) determined a chimney tilt of 45° with an air gap of 200mm and a 1.5m height delivers the maximum flow rate in

an experimental setting. However, Imran et al., (2015) concluded a 60° tilt angle offers the maximum ventilation for a hot dry summer and cold winter periods in Baghdad, Iraq. Jing et al., (2015) and Hou et al., (2019) both looked into a gap to height ratio with 0.5 and 0.4 showing the most airflow rate respectively in an experimental setting. A gap larger than 400mm from the back wall to the glass will lead to a reverse flow (Hou et al., 2019).

Afonso & Oliveira (2000) determined the wall thickness does not have an impact on average flow rates for a Mediterranean climate in Porto, Portugal, but it does affect how the solar chimney operates. Smaller walls shall be used when diurnal ventilation is preferred and thicker walls if nocturnal ventilation is needed and the thermal mass acts as a delay. Exterior insulation around the chimney is required in order to avoid heat losses, even under Portugal's warm climate type.

Harris & Helwig (2007) recommend the use of single-glazed windows as the difference in efficacy with double-glazed windows is negligible and the cost is unnecessary for a

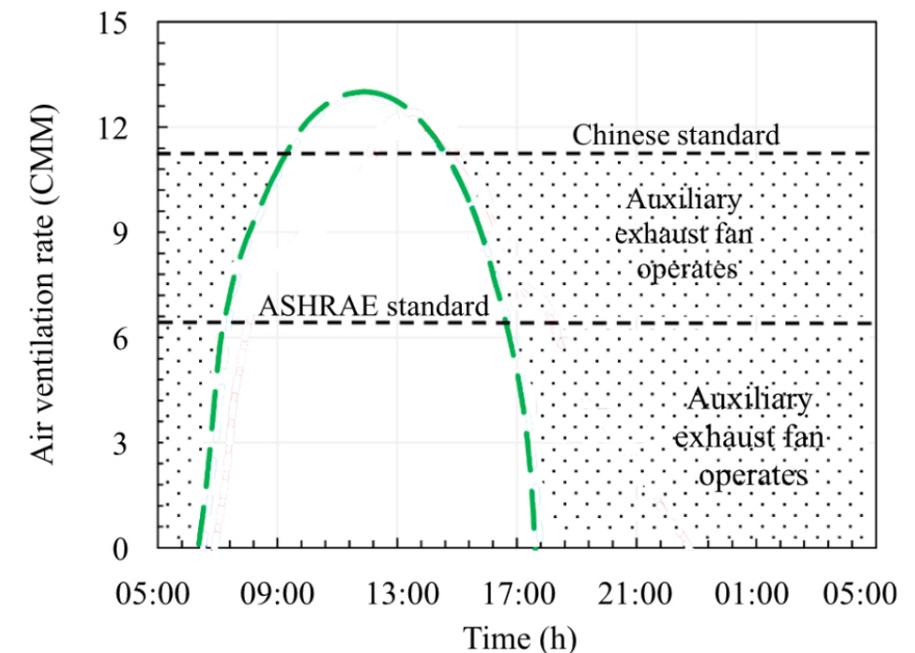


Fig 21: Solar Chimney functioning hours compared to ASHRAE Standard adapted from Salari et al., 2020

temperate maritime climate in Edinburgh, Scotland. The most impactful elements for a solar chimneys operation are section and height (Afonso & Oliveira, 2000) and the impact of wind is negligible. However, the strong dependence on solar radiation to decrease air density means the system requires a specific amount of energy. Al-Kayiem et al., (2014) determined solar radiation over 400 W/m² is necessary for a solar chimney to function correctly in Malaysia's tropical climate. However, this differs from results obtained by Salari et al., (2020) which demonstrate the solar chimney's ventilation rate complies with ASHRAE standards from 7:45 to 16:45 in the subtropical climate of Shanghai, China.

Solar chimneys are good strategies for cooling interior spaces, having various configurations to adapt for different climate types and different airflow and air exchange rate needs. Although highly dependent on the sun, functioning only at specific time frames based on solar radiation and design, solar chimneys are unaffected by other external climatic conditions such as wind or humidity.

| Climate Type | Solar Chimney Type | Reference Papers |
|--------------|---|--|
| A | <ul style="list-style-type: none"> • 3m high • 200mm chanel • inlet and outlet 0.01 m² • 40mm metallic layer • 1 brick layer as structure • Glass wall facing South • Tilt angle: vertical for flat roof or same as sloped roof | Godoy-Vaca, 2017 |
| B | <ul style="list-style-type: none"> • 2.65m width • 1.85m height • Tilt along sloped roof or vertical for flat roof • 280mm air gap • Thin mass wall for quicker ventilation during the day • Glass facing South | Abdeen et al., 2019 Afonso & Oliveira, 2000 |
| C | <ul style="list-style-type: none"> • 200mm air gap • 1.50m height • Tilt along roof slope or vertical for flat roof • Max tilt angle is 60° • Glass facing South • Thick mass wall to delay ventilation • 5cm chimney exterior insulation to avoid heat loss | Afonso & Oliveira, 2000 Chen et al., 2003 Imran et al., 2015 |
| D | Not Applicable | |
| E | Not Applicable | |

Table 8

Solar Chimney considerations per climate type and their reference papers

2.4.6. Shading

Solar shading excludes undesired solar radiation from entering the living space. Window shutters can help with heat retention throughout the night, avoiding heat losses. Shading can be categorized into heating and cooling.

In hot weather climates shading devices prevent overheating from large windows (Looman, 2017). Louver blades or overhangs reduce solar gains during warmer months in residential buildings (Gong et al., 2019). Mashrabiya protect from direct sunlight and soften glare (Bagasi et al., 2021). External shading devices reduce negative influence from solar radiation in the steppe and desert climate of Tucson, Arizona (Khadra & Chalfoun, 2014). However, cooling demand can either decrease or remain unchanged depending on the city. London, for example, does not benefit from fixed sun shading but is impacted over winter months with heating demand increasing (Palmero-Marrero & Oliveira, 2010).

In the arid and temperate climates of Jeddah, Saudi Arabia, mashrabiya allow greater airflow during the day, reducing interior temperature by up to 2.4°C (Bagasi et al., 2021). Although cooling loads decrease, heating loads slightly increase during colder months (Khadra & Chalfoun, 2014). Energy consumption difference becomes a design choice between natural lighting and adequate levels of useful daylight illuminance (UDI). Rooms with mashrabiya show a significantly better UDI than rooms without them (Alelwani et al., 2019).

Mashrabiya regulate humidity through their wooden elements, absorbing and releasing moisture depending on climatic conditions leading to greater interior comfort in arid climates (Bagasi et al., 2021). Coupling a mashrabiya with a wet cloth allows for evaporative cooling, further reducing interior air temperature (Bagasi & Calautit, 2020). The most important factors affecting a mashrabiya's functionality are: shape, aperture and projection.

Mashrabiya



Louvre



Insulates shutter



Fig 22: Examples of shading types used for different climatic conditions

| Climate Type | Shading Type | Reference Papers |
|--------------|---|--|
| A | <ul style="list-style-type: none"> • Balauster Diameter/Length = $\cos(\text{sun altitude angle})$ • Porosity Factor (PF) = y^2 / L^2 to determine how open a screen is • 0.3 porosity factor • 2.40m wide • 3.00m high • If building height > 5.8 mashrabiya is on the second floor and extrudes 0.6m | Samuels, 2011 Bagasi & Calautit, 2020 |
| B | <ul style="list-style-type: none"> • Balauster Diameter/Length = $\cos(\text{sun altitude angle})$ • Porosity Factor (PF) = y^2 / L^2 to determine how open a screen is • 0.3 porosity factor • 2.40m wide • 3.00m high • If building height > 5.8 mashrabiya is on the second floor and extrudes 0.6m | Samuels, 2011 Bagasi & Calautit, 2020 |
| C | <ul style="list-style-type: none"> • If $T_{hot} > \text{or} = 22^\circ\text{C}$ use Mashrabiya • If $T_{hot} < 22^\circ\text{C}$ use insulated window shutters to come close to a wall's R value | Zhou et al., 2021 Quirouette, 1980 |
| D | <ul style="list-style-type: none"> • Use insulated window shutters to come close to a wall's R value | Zhou et al., 2021 Quirouette, 1980 |
| E | <ul style="list-style-type: none"> • Use insulated window shutters to come close to a wall's R value | Zhou et al., 2021 Quirouette, 1980 |

*Text in red is assumed based on recurring literature findings

Table 9

Shading device considerations per climate type and their reference papers

Careful design has to be considered as construction methods provide room for dust accumulation and lead to permeability issues for insects and noise (Bagasi et al., 2021).

In cold climates shadings act as solar collectors, retaining energy throughout the day and releasing it during the night. Window based solar collectors only function in South facing windows in Taiwan's subtropical climate (Chou et al., 2016). Insulated shutters are an effective strategy towards avoiding heat losses (Quirouette, 1980). However, this requires constant human input as maintaining windows shutters closed during the day will prevent heat gains.

Shading devices serve various functions depending on the climate type and design preferences (heating needs or UDI). They maintain thermal comfort but their use has a small impact on the space's livability. It is therefore important to combine shading devices with other passive strategies in order to reduce energy consumption.

2.4.7. Conflicting Strategies

Collaboration amongst passive strategies improves interior comfort and greatly reduces energy consumption. However, conflicting aims are inevitable in highly complex design processes.

Any decision can affect a future decision or diminish its performance if these clashes are not taken into account. Varied climate conditions require specific needs that will improve thermal comfort and reduce energy consumption but design decisions are to be taken that will develop from design preferences or integration of other strategies towards design improvement.

Table 10 is a compilation of potential conflicting strategies per climate type which can arise from the integration of the 6 passive design strategies previously described.

Every design will have design priorities which can be either qualitative or quantitative. Only quantitative design decisions are taken into account in this summary as qualitative decisions differ on a case by case basis. However, awareness of these conflicts is necessary as these will be important design decisions during the design process. Knowing exactly what is being 'given up' in exchange for another choice is valuable information to any stakeholder throughout the design process.

2.4.8. Synergistic Strategies

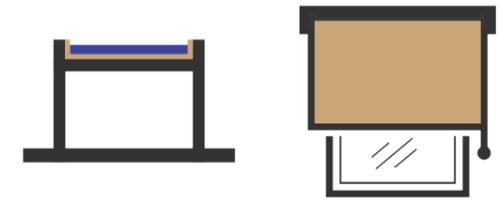
There is great potential towards achieving energy reduction and obtaining thermal comfort by combining passive strategies. Integrating one strategy will improve comfort hours but may not account for all climatic conditions within a region.

Coupling strategies unleashes potential towards higher performing environments and avoids over dimensioning strategies.

For example: A Trombe wall can function as a smaller solar chimney and assist with ventilation. In hot climates this can reduce the number of windows required for ventilation and this reduce unnecessary solar gains.



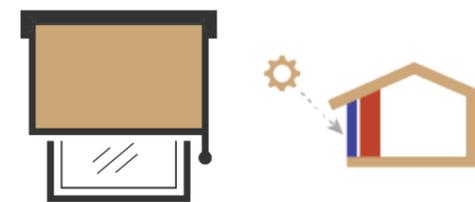
Windcatchers can capture the wind on one end and, through pressure differences, create an interior air flow to ventilate the space. Eg. Summer winds from the North can be pulled by the heat on the South.



Roof ponds benefit from thermal insulation during the day in order to avoid heating, only using them for night cooling. This can be reversed in order to capture heat during the day and store it during the night.



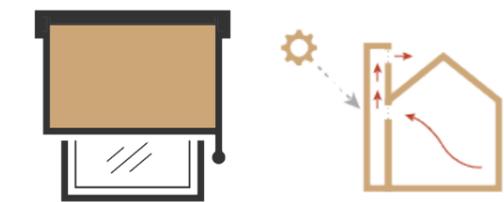
Trombe wall and solar chimney can be combined to increase ventilation in warm climates while delaying heat to radiate into the interior space. This will maintain cool days and warm nights.



Solar shading can prevent overheating of a trombe wall during hot summer days and maintain hot air in the air gap throughout the night during cold winter nights.



If a two sided wind catcher is used, it can capture wind from one end and create a wind flow through the buoyancy effect on its South side. This greatly depends on the direction of prevailing winds.



Mashrabiya and solar chimneys can work together to draw cool air in and extract it on the other side of the room, creating a constant flow of fresh air during hot summer months.



Sunspaces require thermal mass to store all incoming energy from solar radiations. During summer, all ventilation is required to avoid overheating and make the space livable.

| Climate Type | Design Priorities | Passive Strategy Used | Potential Conflicts |
|--------------|--|---|---|
| A | <ul style="list-style-type: none"> Ventilation Large Surface Area:Volume Low window to wall ratio Leightweight structures | <ul style="list-style-type: none"> Windcatchers Mashrabiya | <ul style="list-style-type: none"> Windcatchers are usually built from high mass materials which might not be desirable for periods with low winds and no ventilation Large surface area to volume ratio means rooms are spread, more windcatchers or careful window placement is necessary Low window to wall ratio to avoid overheating will lead to low levels of useful daylight illuminance |
| B | <ul style="list-style-type: none"> Ventilation Reduce temperature gradient Low window to wall ratio Large Surface Area:Volume | <ul style="list-style-type: none"> Windcatchers Trombe wall Roof pond Mashrabiya Solar chimney | <ul style="list-style-type: none"> Large surface area to volume ratio leads to a greater number of passive strategies required for ventilation Trombe wall and roof pond will delay the transfer of heat during the day but mashrabiya and windcatchers are 100% wind dependent Reliability on solar chimneys for ventilation under low wind speed conditions |
| C | <ul style="list-style-type: none"> Heat is required during winter periods and ventilation during summer Reduce temperature gradient Energy conservation | <ul style="list-style-type: none"> Sunspace Trombe wall Solar chimney Sun shading | <ul style="list-style-type: none"> Higher ventilation needs over the summer for cooling can impact illuminance levels if mashrabiya are integrated Thermal buffering from trombe walls or sun shading devices can impact natural illuminance levels Integrating passive strategies for ventilation leaves little possibilities to change layout during the operational phase |
| D | <ul style="list-style-type: none"> Heat retention Solar heat gains needed Compactness Interior thermal mass | <ul style="list-style-type: none"> Sunspace Trombe wall Insulated shades | <ul style="list-style-type: none"> Windows are required for solar gains but these also become heat loss surfaces Low mass buildings heat up quicker during the morning but do not retain heat for long after the sun sets Skylights offer more light during darker months but they require extra insulation |
| E | <ul style="list-style-type: none"> Wind protection Solar heat gains Compactness Heat retention | <ul style="list-style-type: none"> Sunspace Trombe wall Insulated shades | <ul style="list-style-type: none"> Same as above climate type D Pitched roofs for snow control impact room compactness Airtight buildings will prevent heat losses but air exchange will have to be solved differently |

Table 10

Conflicting quantitative strategies based on climate type in relation to the six passive design strategies previously described.

OPTIMIZATION WORKFLOW

3.1. Introduction to Computational Workflows

3.2. Single vs. Multi-Objective Optimization

3.3. Effective Optimization

3.4. Importance of Problem Formulation

3.5. Data Generation

3.6. Parametric Dialogue for Bioclimatic Design

3.7. Workflow Definition

3.8. Computational Assisted Design

3.1. Introduction to Computational Workflows

Defining Optimization

Architecture has developed as a design process stemming from a need to satisfy specific requirements. As a process, architecture begins with a site analysis and research into local conditions under which the new construction will have to cohabit. An inhabitable design contains desirable configurations or situations offering adequate living conditions. An optimum configuration contains the most desirable characteristics for a defined space (Canestrino, 2021) and indicates there is no possibility of improving such a characteristic based on the chosen adjustable characteristics.

Optimization simulations operate by searching for minimum or maximum values for a specific characteristic. If an architectural form is defined with specific parameters (eg. width, length and height), it is possible to optimize the form based on the initial parameters in relation to an optimization characteristic (eg. building volume) (Canestrino, 2021). However, the optimal parameter value will only be relevant under the desired optimization characteristic and vice versa.

Optimal solutions are not optimal buildings. It is the relationship between a parameter and a design goal which are pre-defined prior to a simulation process. However, optimizing for a specific goal might neglect or negatively impact other building characteristics.

When optimizing for two or more values it often becomes difficult to form a relationship between building characteristics (Wetter, 2000) and understand where a positive or negative impact might be derived from. Computational Design Exploration is the process of extracting useful information from simulations and data sets (Yang et al., 2020) that will assist towards improving a designs characteristics or operations.

Uses for Optimization

Buildings are complex systems having a manifold of characteristics which can be optimized for, such as cost, area, comfort, energy, etc. and used to achieve optimal designs which satisfy performance requirements (Yang et al., 2020). There is ample research done within architecture aiming to define optimal solutions to specific scenarios. González and Fiorito (2015) looked at louvre geometry optimization for office buildings demonstrating an improvement in daylight illuminance distribution. Giouri et al. (2020) determined the best location for solar panels, determined building characteristics to reduce energy consumption and improve thermal comfort through optimization simulations. Vighnesh et al. (2021) looked into the best conventional material choice combinations for walls, roof, floor and window when compared to a conventional construction. Manni et al. (2020) looked into volumetric design improvements for a Nordic and a Mediterranean climate zone regarding solar irradiation.

A design concept can be explored in many ways, from a subjective perspective to an objective achievable goal. Computational design explorations evaluate optimization solutions which best fit the requirements to solve a design problem (Yang et al., 2018). Results obtained from optimization simulations, especially with multiple variables, can widely vary and might be inconsistent with previous simulations. Optimization workflows should be seen more as design tools for inspiration rather than final design characteristics (John Frazer, 1995). This is especially relevant in early design stages when designers are still researching into the design task, the site and its climate. The limited knowledge at initial stages can benefit from data obtained through optimization workflows to grasp a range of potential characteristics to tackle a design problem or need (Yang et al., 2018).

Types of Workflow

There are various types of workflows in which optimization can be integrated as a strategy towards design exploration. Regardless of how or where optimization is inserted, there is always one thing in common: the workflows require an iterative process under which an optimization simulation can run. It can be considered as a fast-paced trial and error where the algorithm determines if the results are headed in the right direction or if it should modify the parameters differently to obtain the desired result.

Building Energy Modeling & Simulation software is used to evaluate a building's performance. Data obtained from this software can be used to define parametric configurations for specific buildings. The dialogue between building energy modeling & simulation software and optimization simulations is described in Fig. 24 (Barber & Krarti, 2022). The process aims to achieve specific design goals, if results are not obtained, there is an iterative loop. If results are achieved the design and its characteristics are compliant and stop the optimization process.

A workflow proposed by D'Agostino et al., (2021) is a Computational Performance-Driven Design Optimization. An initial building is designed with determined modifiable parameters and is analyzed based on performance. Fitness objectives are the elements for which the optimization is being simulated; these can be organized in terms of priority to verify if a design satisfies its criteria. The simulation runs in an iterative loop, learning from previous results and creating crossovers between parameters to develop the optimal solution defining the models modifiable parameters (Fig. 25). Optimization processes will run until the simulation is stopped or when all options have been tested. All data is recorded and stored for later visualization.

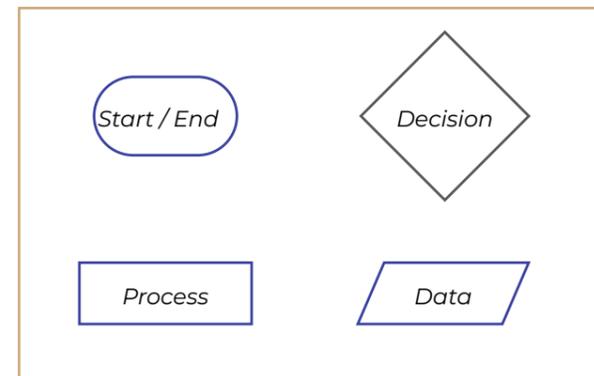


Fig 23: Symbol convention used in flowcharts

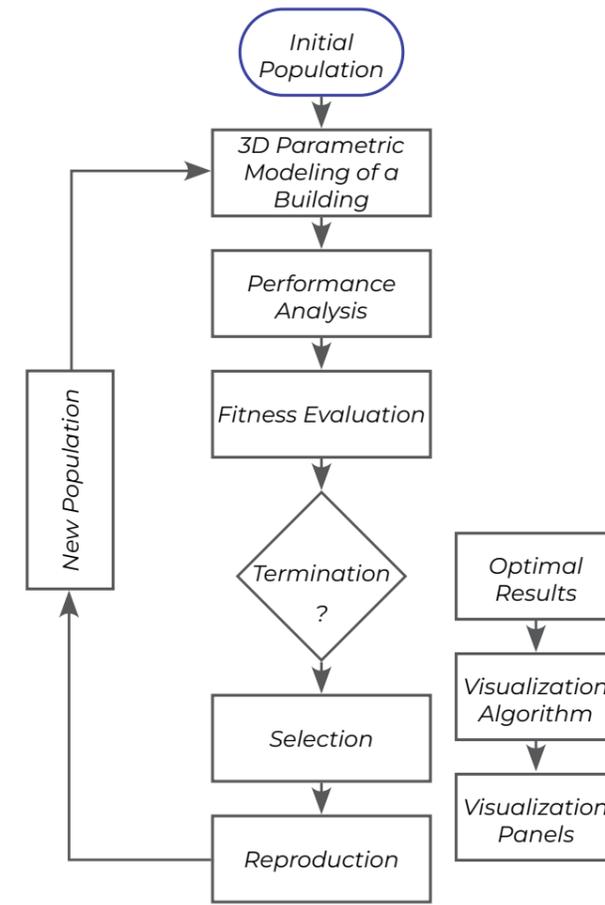


Fig 25: D'Agostino et al., 2021. Computational performance-driven design optimization

Yang et al., (2020) emphasize the importance of knowledge acquired throughout the optimization process. When optimizing towards an objective, it is important to gather information on a design's affecting factors. Initially, there is a problem which has to be solved, optimization is used to tackle the problem however, other trade-offs might occur which will have an impact on a different building characteristic. As such, an optimization problem re-formulation is required prior to defining an optimal solution to a problem (Fig. 26). In order to acquire knowledge the optimization process will have to break down into segments where both quantitative and qualitative data are used to re-formulate the problem prior to continuing the optimization process.

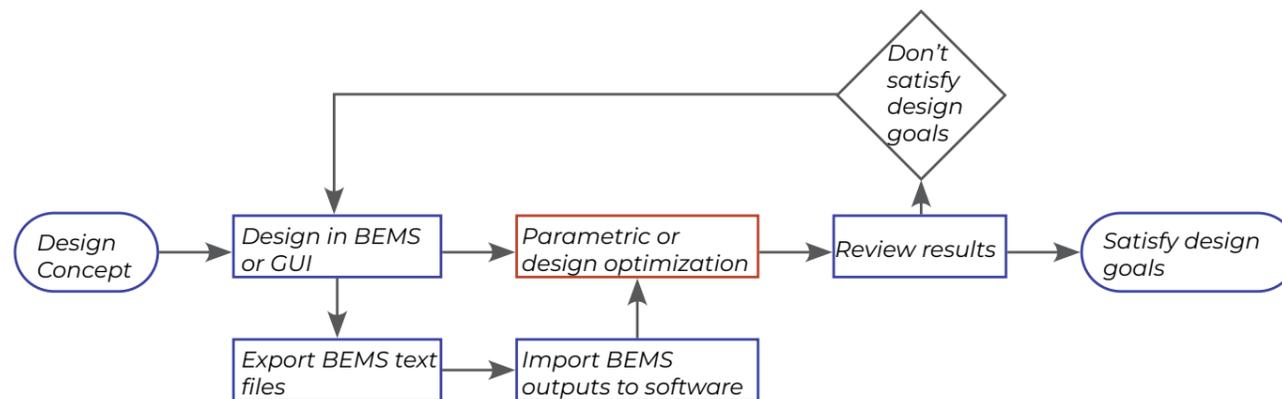


Fig 24: Barber & Krarti, 2022. Relationship between building energy modeling & simulation software and optimization simulations

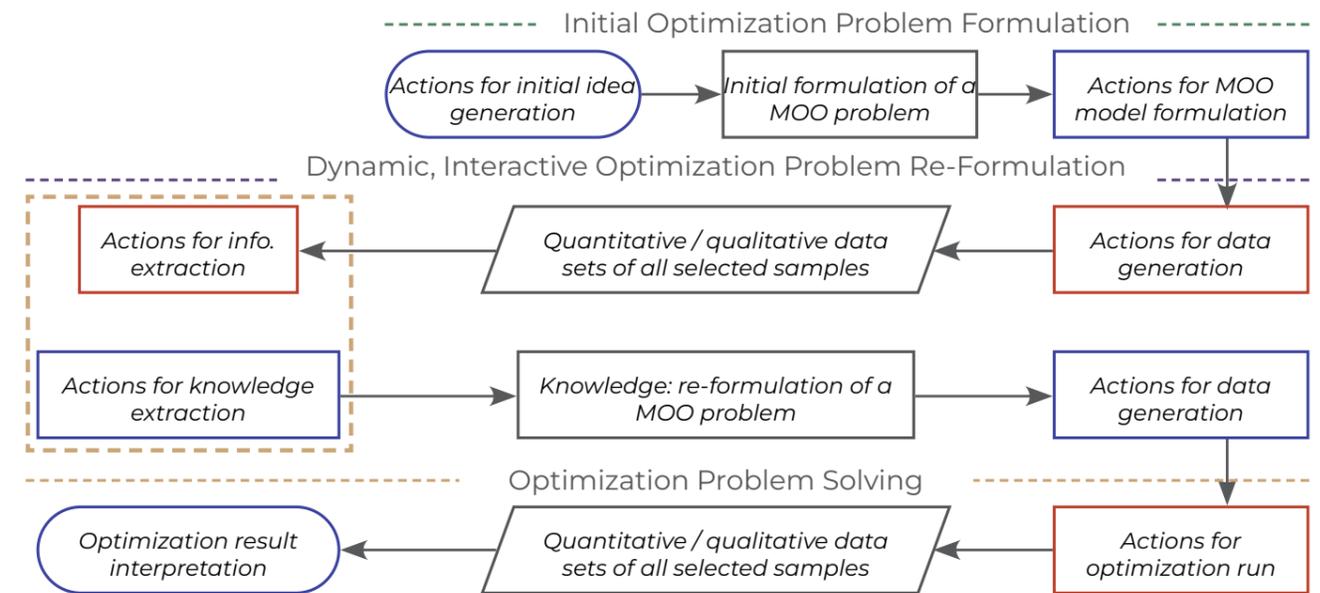


Fig 26: Yang et al., 2020. Problem Re-Formulation workflow

Stages at which Optimization is Used

Much of the research carried out in sustainable developments or improvements towards energy reduction revolves around buildings and large scale typologies; primarily for already completed projects. Optimizations focus on the premise that such buildings are already designed and the alterations occur at a façade level, either through sun shading devices (Sheikh, 2011, González and Fiorito, 2015) or materials and fenestration (Laouadi et al., 2002, Jalilzadehazhari et al., 2019 & Vighnesh et al., 2021).

Yang et al., (2018) looked at a multi-objective optimization of a sports hall, considering design criteria for usability, thermal comfort and structural viability. In this case, optimization occurred at an earlier design stage where decisions could be taken prior to the final construction. However, a developed design was already presented as an optimization case.

Many optimization cases, especially single-objective optimization, require a project to be built in order to assess its shortcomings, and offer potential solutions towards already existing problems. This is highly effective for projects which are already built and aim to reduce their energy consumption according to The European Green Deal (European Commission, 2019); where all buildings are to become near-zero energy consumption buildings by 2050. However, buildings for which construction has not begun have no clear method to analyze potential design solutions or variants.

Early Design Stage Optimization

In order to reduce energy consumption in new constructions it is necessary to address the energy hierarchy from the top, therefore reducing operational costs and the need of investment into technological solutions in the future. As such, considerations are to be taken from the early design stages, as opposed to analyzing for renovation, in order to create a design that will respond to climatic and social needs.

Early design stages are project phases where the design is still under exploratory development. This can be initial design sketches, conceptual design and even a schematic space distribution. The importance of an early design stage is the ability to quickly change and drastically modify a design without creating major disruptions in the design workflow.

Improving energy efficiency in the initial design stages through the use of computer aided design tools is possible. Belmonte et al. (2021) experimented with an early design stage tool to define schematic designs for a small house. In all instances students utilizing the tool to guide design, developed schematic

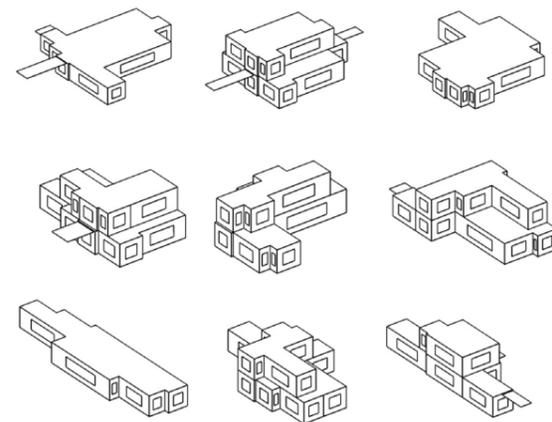


Fig 27: Granadeiro, V. (2013). Building envelope shape design in early stages of the design process: Integrating architectural design systems and energy simulation

designs best suited for the project location. Granadeiro et al. (2013) developed a methodology assisting in the decision making process towards a buildings' geometry. Based on grammar rules, the space grew based on a rooms function and its proximity to a fireplace. The model is based on the relationship between design parts which have an impact on the subsequent growing sequence.

Although there are some design limitations with the method, having an approximation to a buildings energy demand is sufficient for the level of detail in early design stages (Granadeiro et al., 2013).

Information from Optimization

Optimization results are comparisons between various iterations with sorted resulting values. Baglivo's et al., (2014) research into building skin reinforces the fact there is no optimal solution but a range of possible outcomes.

Gasparella et al., (2011) defines multi-objective optimization results as the trade-off between various outcomes.

There is no "optimal" solution, the integration of a design decision may have an impact on other design characteristics, even ones which are not being accounted for and quantified.

From the research studied regarding optimization workflows and methodologies only 30% of the studies implemented optimization strategies at early design stages.

Optimization workflows have been proven to work at early design stages, focused on various design aspects impacting the final outcome. Considering Evans, J.M. (2007) stage implementation graph, early design modifications have a more potential and lower costs, benefiting the project's outcome.

As Yang et al., (2020) also stated, the knowledge acquired at various stages is necessary to develop the design. Knowing early on the design constraints and correlating parametric changes to building impact is necessary to take informed decisions throughout the design process.

Having design knowledge acquired at an early design stage allows more drastic modifications to a design. Based on qualitative and quantitative data several alternatives can be formulated and the implementation strategies are not constrained to a specific facade or structure.

3.2. Single vs. Multi-Objective Optimization

The search for optimal results can be carried out through a single objective approach or a multi-objective approach. Single objective optimization considers one or more genomes but only one fitness objective. Multi-objective optimization considers one or more genomes and multiple fitness objectives. Objectives can be either minimized or maximized and will guide the optimization algorithm process accordingly.

Single-Objective Optimization

Single objective optimization has a faster computational time to reach a desired result as there is only one objective and the algorithm can focus on either reducing or maximizing the value. With a multi-objective simulation there is added complexity as the genomes affect the fitness values in different ways. In the complexities of a building system a modification in one aspect might have a negative impact on another. For example, increasing a window size improves natural ventilation but might also lead to light overexposure, reducing UDI.

Multi-Objective Optimization

Buildings are complex systems depending on several factors to function appropriately. When only optimizing for one fitness value it is difficult to notice the impact some design alternatives

have on other building characteristics. A multi-objective optimization approach offers the possibility to focus on design priorities. These design priorities are usually requested by the client or the user and give way for a tailoring of the design in accordance to specific needs. If there is a preference for natural lighting levels over thermal comfort, fitness values for the natural lighting fitness objective can be chosen accordingly.

The benefits of using a multi-objective optimization approach are the knowledge acquired from the optimization process but also from the fitness value selection. Understanding there is a potential trade-off between illuminance levels and thermal comfort can prepare the user to consider other design strategies to improve thermal comfort. Having a choice between one fitness objective and the other offers greater control into qualitative design decisions.

In comparison, a single-objective optimization will only offer knowledge based on a single characteristic. There is little to compare or contrast and as such, the design possibilities become limited. A multi-objective optimization workflow is therefore, as John Frazer (1995) mentioned, “a tool of inspiration”. The choices available inspire the creativity and develop our knowledge towards a better informed design process.

| Optimization Type | Genomes | Optimization Time | Fitness Objectives | Cause & Effect | Use | Information Visualization |
|-------------------|------------------------------|-------------------|---|---|---|---|
| Single-Objective | At least 1, can include many | Fast | 1 | Hard to determine as other factors might have an impact | To either minimize or maximize a specific function | Line graph with fitness value change |
| Multi-Objective | At least 1, can include many | Slow | At least 2, can include many, for better results no more than 4 | It is possible to define after several iterations | To obtain a range of potential design possibilities | Parallel coordinate plot, pareto front graph, diamond graph |

Table 11

Comparison table between single and multi-objective optimization

3.3. Effective Optimization

Computers are powerful tools being used for design and design simulations, allowing the gathering of information and up-to-date building data, facilitating the execution of projects by having precise digital representations for the building. There is a large amount of data stored for a building and with tools such as Grasshopper’s Ladybug and Honeybee, more information can be derived from a building’s operation.

Generated data can be used to form knowledge-based design approaches, leading to a better understanding of a project’s performance. Optimization workflows are often used to find optimal solutions, in the form of parameters, to specific design requirements.

Optimization Parameters

Parameters used to operate and manipulate a design’s characteristic are called genomes (forming the genetic makeup of the building). Characteristics which are being optimized are defined as Fitness Objectives and the fitness values are the results obtained throughout the optimization process. The resulting geometry from an optimization process is defined as a phenotype.

A optimization algorithm is taught to find the minimum or maximum value achievable under specific design constraints. Through mutations and crossovers between simulations, the algorithm looks for the best fitting combination of genomes to achieve the highest or lowest fitness value result. Optimization workflow serves to efficiently define an optimal solution to a design constraint.

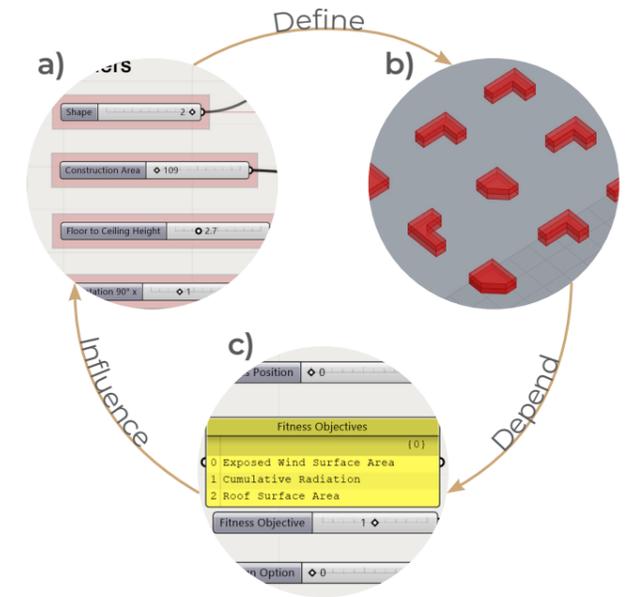


Fig 28: Design parameter relationship. a) Genomes, b) Phenotypes, c) Fitness Objectives

Importance of Site Information

Knowledge based decision-making is key towards creating a design compliant with performance requirements. Climate specific conditions have an impact on how we want buildings to perform under specific weather and seasons. A summer and winter climate in Singapore might be similar, given its proximity to the Equator but this is not the case for Stockholm. When a project located in Stockholm is designed to maximize natural ventilation this will certainly improve thermal conditions during summer but would worsen them during a winter period.

Running simulations and subsequent optimization towards maximizing ventilation for a project in Stockholm is therefore unnecessary. However, if the time period is analyzed specifically for a summer period, this will result in information that can be acquired. The genomes obtained from such a simulation would have to be compared to a winter situation to see if it impacts positively or negatively in the design.

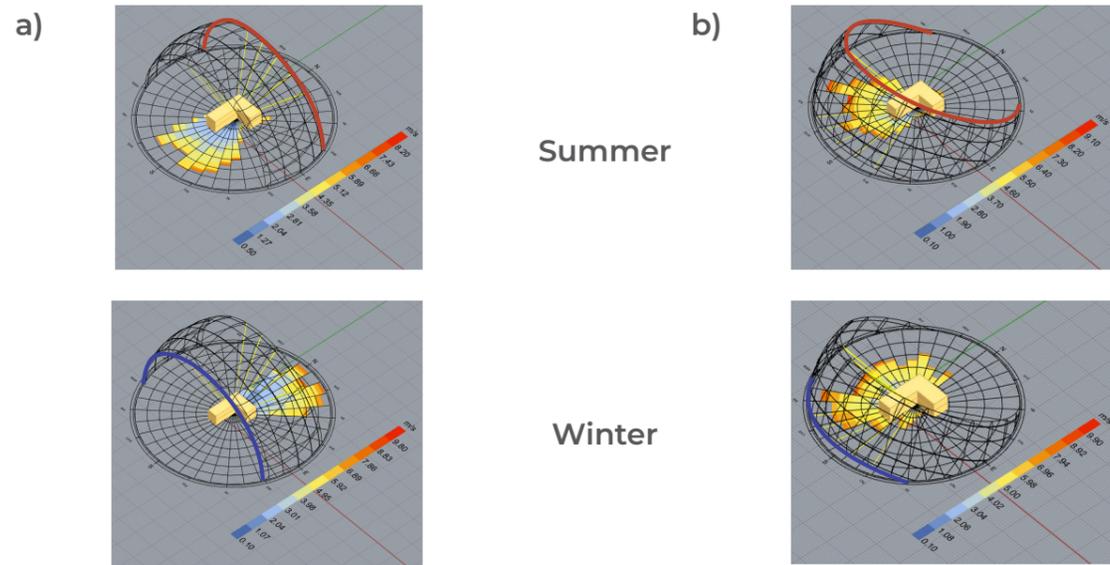


Fig 29: Comparative solar path between a) Singapore (summer and winter) and b) Stockholm (summer and winter)

Tactical Requests for Optimization

Given the nature of how optimization algorithms work, there is a trial-and-error process in which the algorithm rearranges the genomes and evaluates the fitness value. To reduce computational time and improve the results in the direction required or under / over a specific threshold, penalties can be implemented to indicate what direction the algorithm should continue its exploration.

Useful Daylight Illuminance is the percentage of occupied hours that illuminance falls between a minimum and maximum threshold. An adequate UDI would be over 80%, meaning that 80% of the time there is adequate illuminance in a space. Knowing this threshold allows adding penalties to the optimization

process through conditional formatting. If UDI is below 80%, the resulting fitness value becomes extremely small. Since we are aiming to maximize the UDI, the algorithm will determine the previous genome modification severely reduces UDI levels and will readjust accordingly.

Through this strategy, UDI level results will mostly fall between 80% - 100% since the optimization algorithm learned anything below 80% is not desired.

Arranging the optimization process to focus on desired outcomes reduces computational times to achieve specific fitness values. The data obtained through optimization will be richer as the values obtained will be above or below specified thresholds, instead of a wide spread of results. The genome pool becomes more focused towards achieving design goals and prepares a better phenotype for future simulations and the next optimization phase.

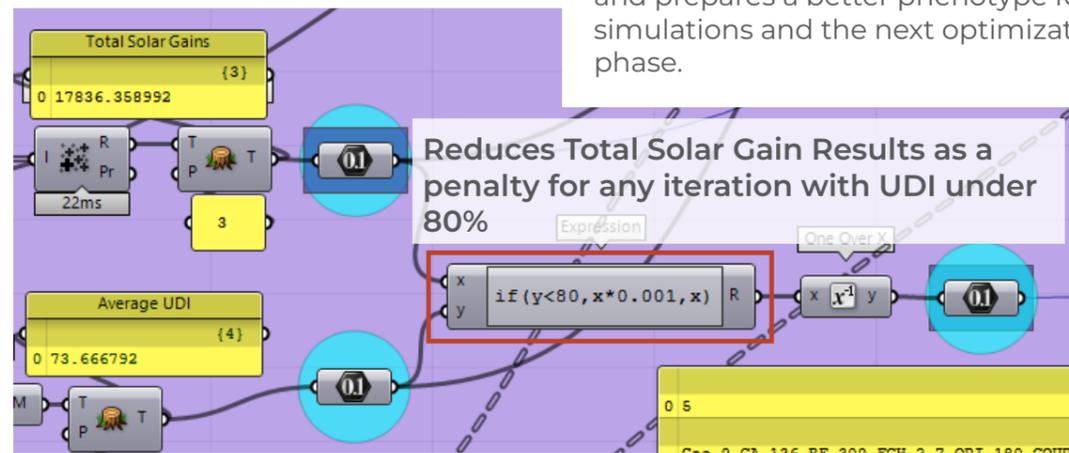


Fig 30: UDI Constraints to maintain results above 80% UDI

3.4. Importance of Problem Formulation

The availability of design choices is a key step in an optimization workflow. Choices give way to human input which demonstrates a design preference between a chosen geometry and another. This dynamic interaction between humans' qualitative choices and a computer's quantitative data improves a building's operations whilst satisfying user preferences and priorities.

Knowledge Acquisition Steps

Through a stepped optimization workflow, where problem re-formulation can occur, it is possible to select appropriate design genomes which perform well under various conditions. A qualitative and quantitative exploration allows gathering the necessary knowledge to define a functioning phenotype which can be used for a more detailed exploration. The remaining phenotypes, which are not qualitatively preferred are exempt from future simulations, thus reducing simulation time and focusing optimization processes on designs that are most likely to satisfy design criteria.

Comparing vs. Optimizing

Although an optimization process is a key component in achieving an optimal result to a specific criterion, optimization simulations tend to be time consuming. It is not recommended to run simulations whilst taking part in a collaborative design session as there is no human input during the process. Optimization simulations are set and supervised by a building engineer or an architect, sharing the results post-completion.

To achieve collaborative design there is an input from all parties involved with a common objective. In order to continuously gain input and be able to analyze different geometry types it is possible to generate design options and compare their results. A distinction

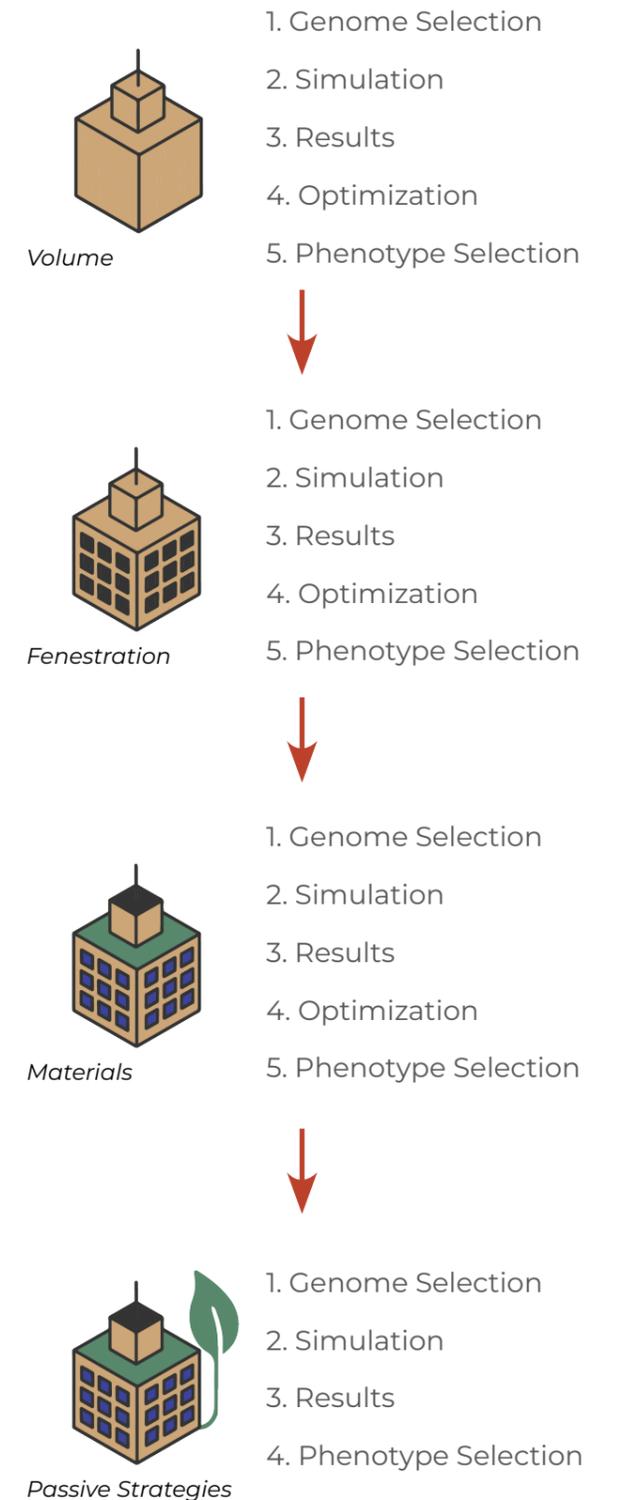


Fig 31: Schematic diagram of the proposed stepped approach

is therefore made between multi-objective comparison and multi-objective optimization.

Both systems function exactly the same when choosing genomes and fitness objectives, the only difference is when comparing simulation results. For a multi-objective comparison, the results are compared amongst the selected choices, recording the genomes and fitness values in a database. The comparison occurs amongst the number of selected possibilities where data is presented side by side to evaluate design choices

according to the selected criteria and design priorities.

Optimizations are not generated within a multi-objective comparison process due to time constraints. Instead, the data obtained from simulations based on the fitness objectives is used to guide the design process. Qualitative preferences and data comparison are the main drivers through the step-by-step process. This gives more control over the design choices and facilitates the gathering of knowledge that will be used to define future design stages.

Multi-objective optimization takes an initial design and modifies its genomes to either maximize or minimize the fitness values. This process is automated and does not require qualitative input. There is no need for human presence throughout the process and would therefore be unnecessary during collaborative design. However, the design variations obtained from an optimization process can show significant improvement in fitness values to the designs generated through the multi-objective comparison process.

The multi-objective comparison process can be viewed as the initial ideas stage, a general exploration into geometries, their genomes and the potential fitness values. Through a stepped approach and collaborative design, the process will develop user knowledge, ultimately to reduce energy consumption, improve thermal comfort and create comfortable interior living conditions.

Comparison to Optimization

There are two potential workflow mechanics under which the multi-objective comparison and multi-objective optimization assist the design process. If a multi-objective optimization is simulated prior to a multi-objective comparison, data gathered from a preliminary optimization can guide design through previously acquired knowledge.

This process requires the knowledge of site and plot area prior to optimization. However, since the design process developed as a stepped approach, it will only run on the most optimal results obtained for specific fitness objectives. Optimization simulations therefore completely avoid qualitative inputs as a design process. On the other hand, the results obtained will be closer to the optimum for a specific design criterion.

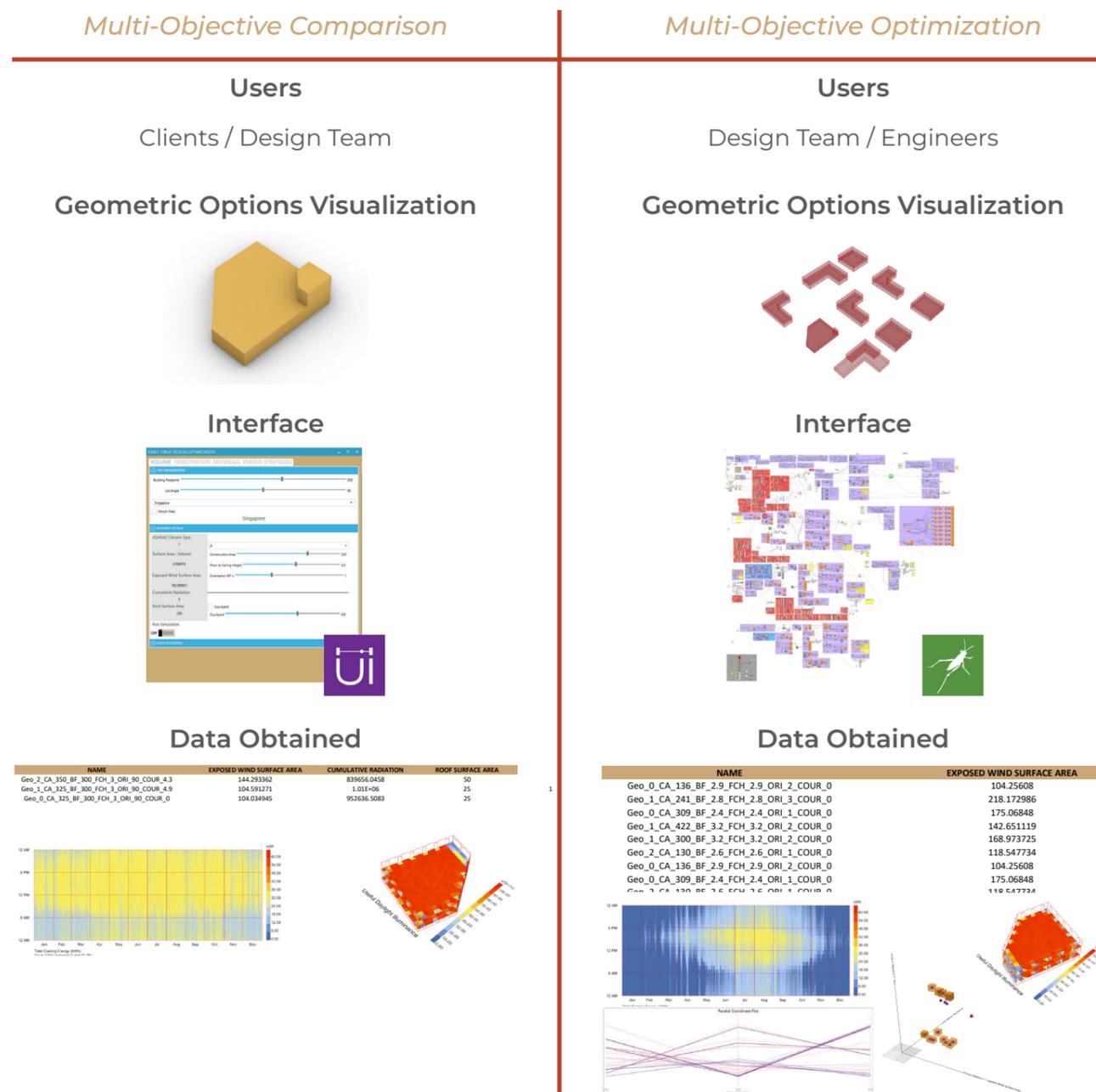


Table 12

Comparison table between multi-objective comparison and multi-objective optimization

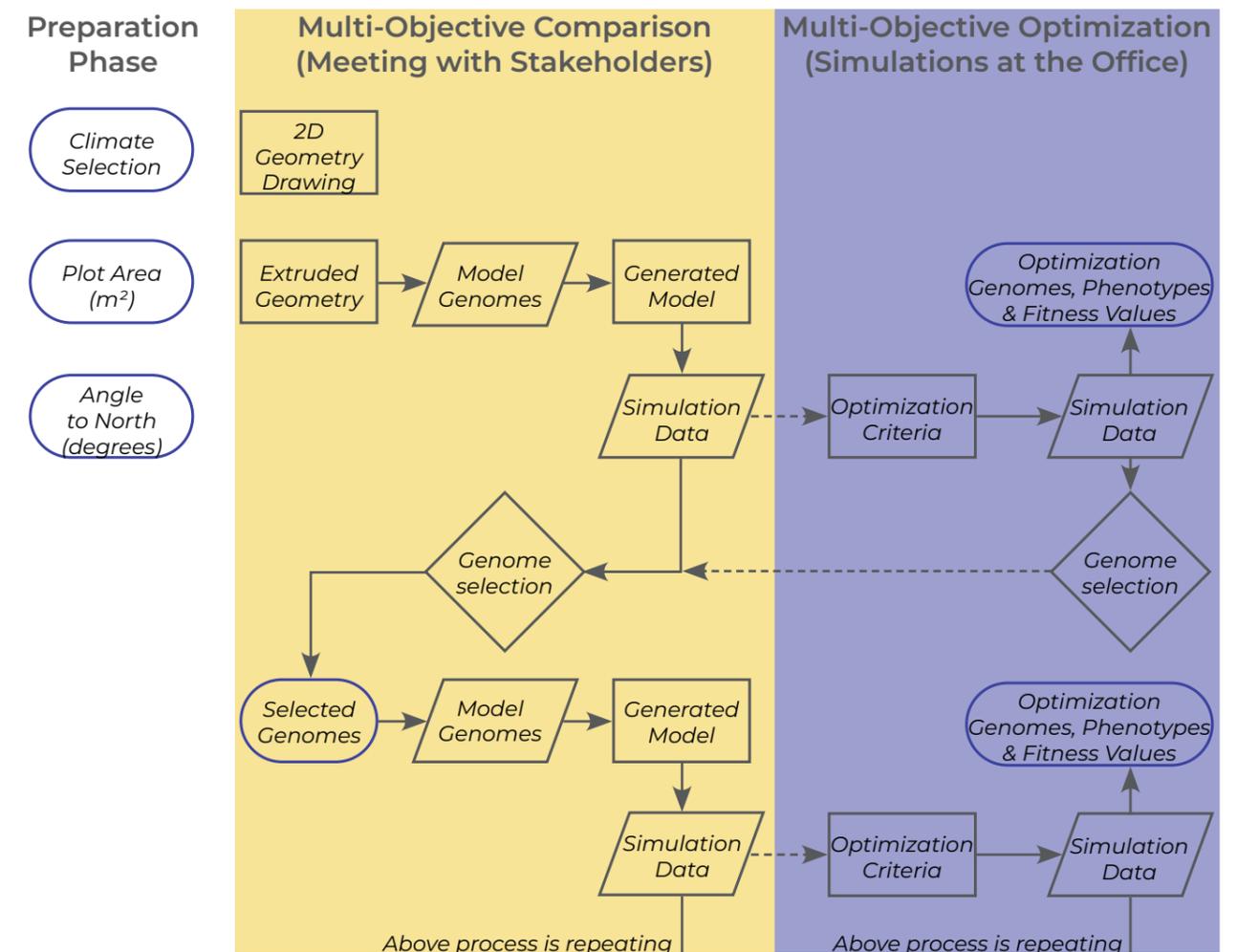


Fig 32: Workflow for multi-objective comparison preceding multi-objective optimization

Optimization to Comparison

Comparatively, when the multi-objective comparison process is done prior to optimizations, there is a larger qualitative input from the user. Preferences are being discussed and the creative possibilities are not limited by trying to approximate the optimal outcome. Furthermore, data obtained from a multi-objective comparative process can be utilized to define optimization penalties when the optimization phase begins. Since the aim is improving the results based on specific criteria obtained through a comparative process, the numbers can be set as minimum, when wanting to maximize a value, or a maximum, when wanting to minimize that fitness value.

Using results from the multi-objective comparison process to define result thresholds will focus the algorithms search to a more concrete outcome. This will ensure that an optimization simulation will not provide random values but concrete, knowledge-based improvements.

Both approaches are valid options, it highly depends on user preferences which are chosen. Some might prefer a more hands-on approach while others might want to focus completely on optimal solutions for a specific design criterion. The workflows flexibility allows for either integration into the design process. In both cases, the outcome will show improved results in one field or another according to user preferences and design needs.

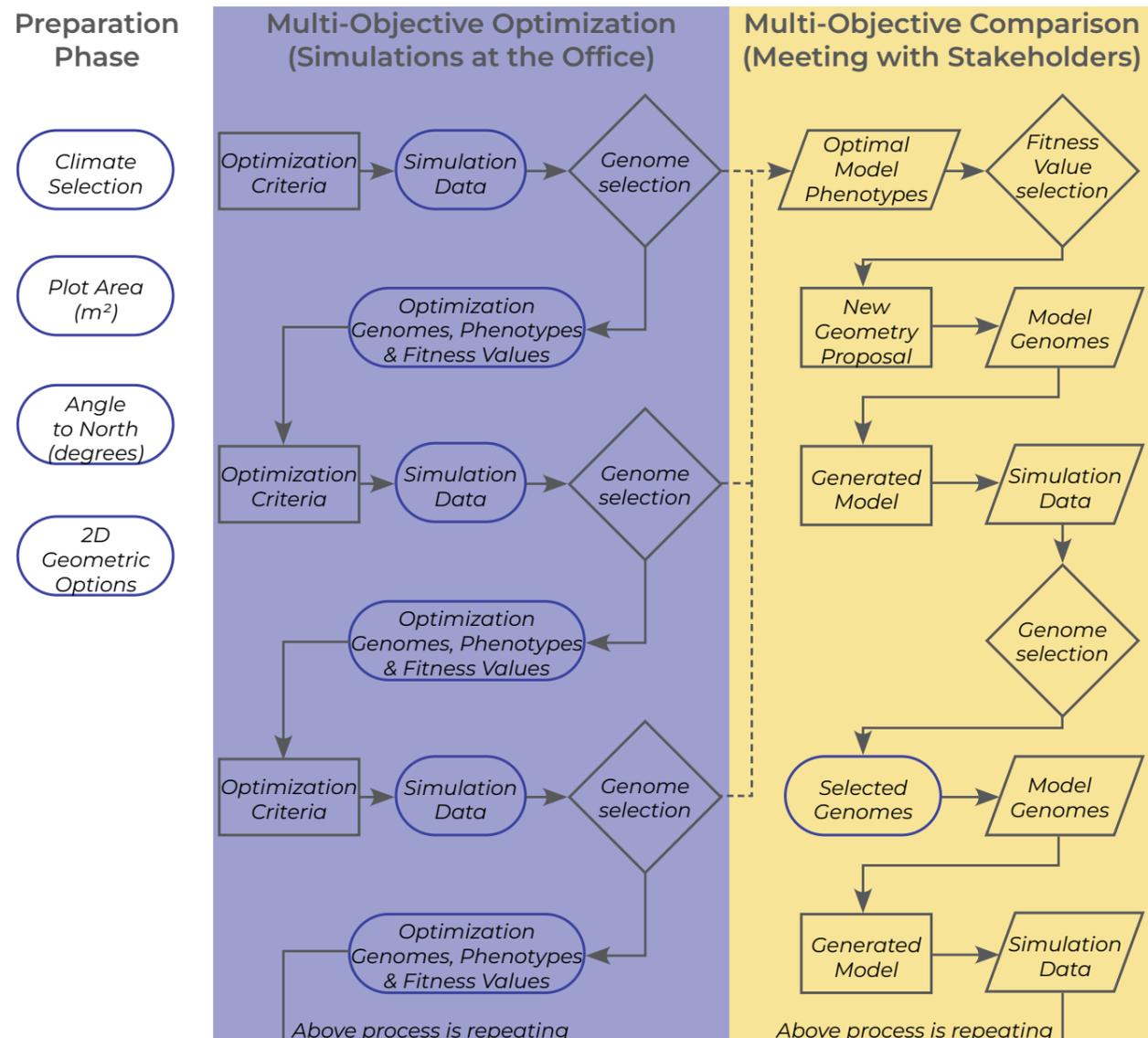


Fig 33: Workflow for multi-objective optimization preceding multi-objective comparison

3.5. Data Generation

Knowledge acquired throughout the process is used to determine the next steps and design adjustments. For instance, during the multi-objective comparison process at the volumetric level, a geometry is chosen with a worse thermal performance than its comparative geometry. The user has a choice to either reduce or increase window size area at a fenestration level or improve thermal performance at the material level. Both actions will lead to an improvement in thermal performance, albeit to a lesser degree than if the better situated geometry had been initially chosen.

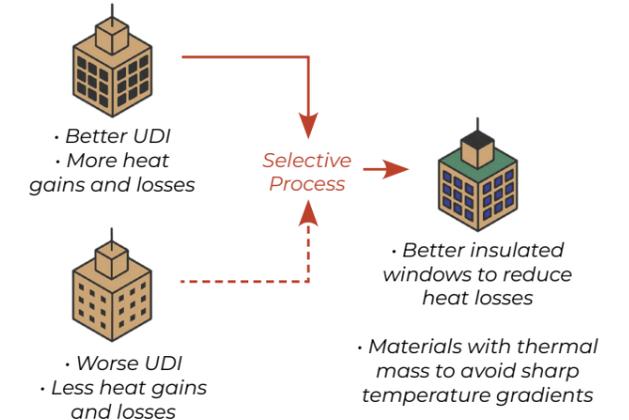


Fig 34: Example of a selective process through a stepped approach

To trace back these decisions, data recorded from the simulation procedures is stored in a database. Having access to such data gives the possibility to retrace design history and verify at what stage improvements can be made. The database is separated into two processes, the multi-objective comparison and the multi-objective optimization. In both cases, storing the acquired data is manual, giving the user control over what data is actually considered for comparison.

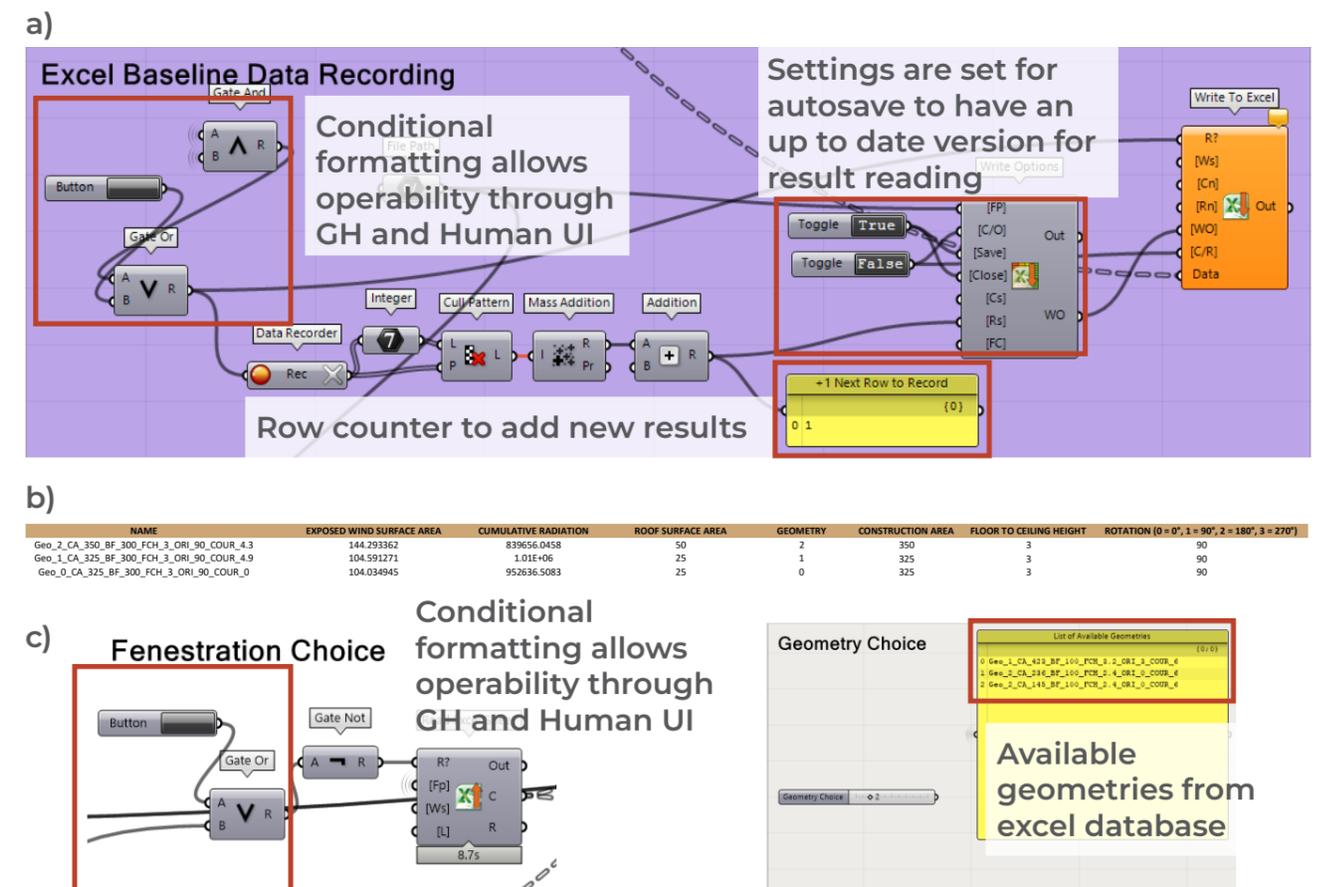


Fig 35: a) Data manual storage process in Grasshopper b) Excel tables with data and results which can be called upon c) Data calling process in Grasshopper

For a comparative process, the data is retrieved and compared on a real-time basis. Graphs are generated for each iteration in order to compare performance criteria throughout the process. During an optimization process, 72 different iterations are stored in the database.

Wallacei Grasshopper plugin is used for a multi-objective optimization with a generation size of 6 and a generation count of 12. These parameters were chosen to reduce time constraints throughout the optimization process. Data visualizations for all 72 iterations is not provided however, individually selecting any iteration from the optimization process is possible. A 3 x 3 grid of design options is generated from the optimization process based on fitness objective and fitness value rank.

As some optimization objectives have similar results, there are several design options to choose from. From the grid, a qualitative selection can take place. The iteration is selected and recorded into the comparative process database which can be used as a benchmark for comparison.

Such a database process was developed to offer users more control over which geometries to compare, reducing the number of potential outcomes and only focusing the selection based on a fitness objective which is defined by the user's design priority.

Constructing a database assists throughout the current design process, also having the benefit of utilizing the acquired data for future projects in similar climate regions. Although comparing a project's results with a different project is not recommended, due to distinct variables, a tentative benchmark can be helpful to guide the design process. This has the same effect as introducing the optimization results prior to the comparative design process.

In general, the more information is stored and used throughout the process the more knowledge is acquired to take educated decisions. There is a need to filter information to avoid overwhelming users with data and focusing on information relevant to a selected design criteria.

Multi-Objective Comparison

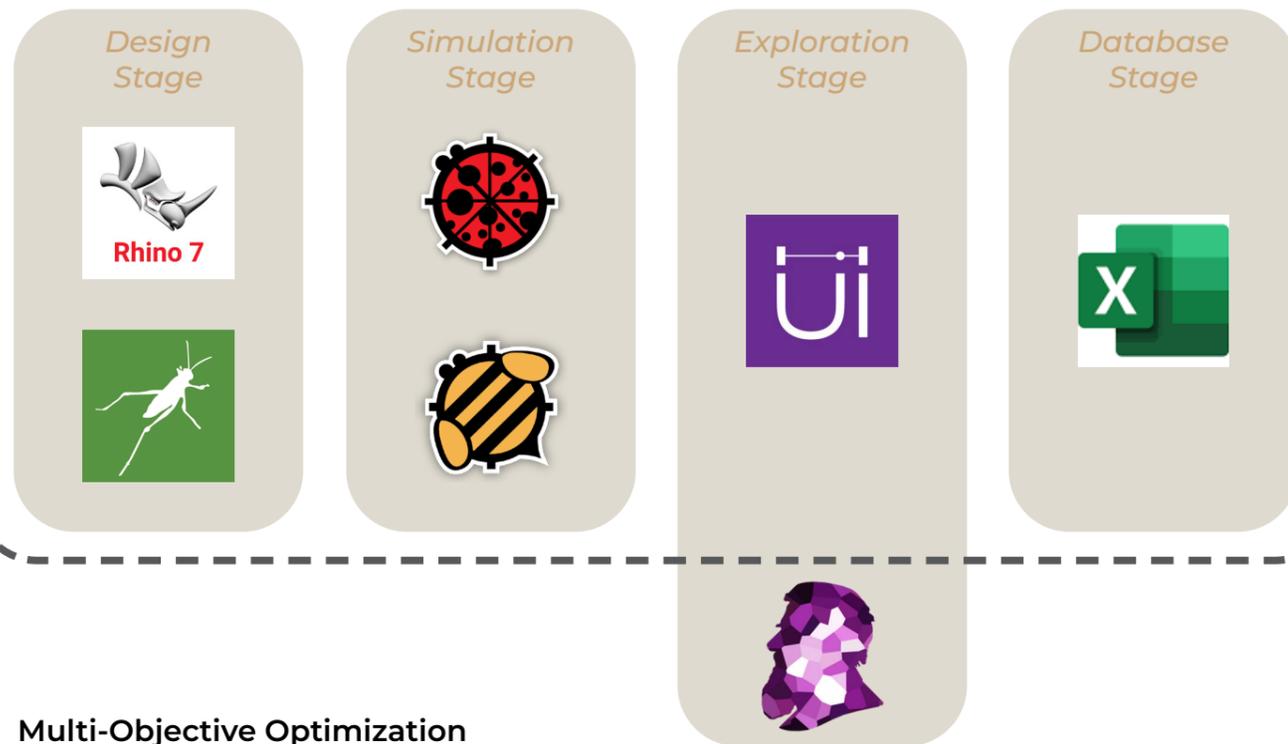


Fig 36: Software repertoire to generate data and their relationship to a multi-objective comparison and multi-objective optimization process.

3.6. Parametric Dialogue for Bioclimatic Design

Creating a multi-objective workflow that allows knowledge development throughout the design process required separating design stages into manageable sections with independent genome control. Segmenting the workflow permits correlating the modifications from specific genomes with the fitness values obtained. If too many genomes are present within one segment, the correlation becomes harder to define; thus, knowledge is not obtained.

The proposed workflow is segmented into three stages, volume, fenestration and materials. Each stage has a similar workflow starting with model development, genome selection, simulation process, result recording and optimization process. The selected genomes are either extracted from the comparative model or an optimization analysis.

Workflow Concept Design

To develop a working model towards a volumetric study, an input has to be generated in the rhino interface as a geometric extrusion.

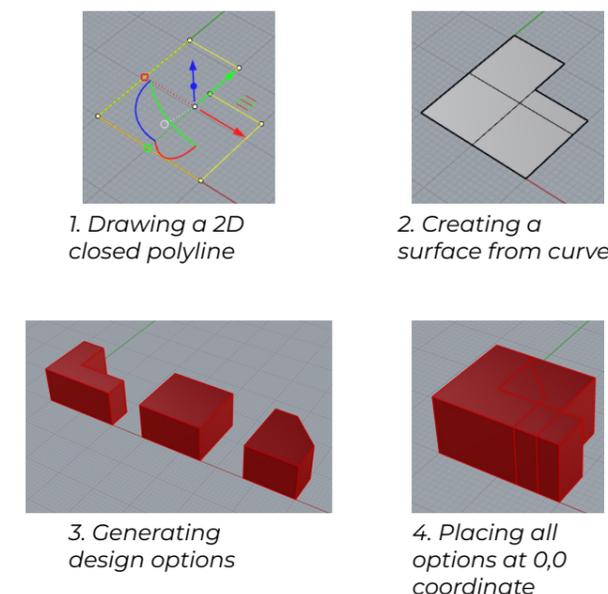


Fig 38: Geometry drawing in Rhino 7 process and extrusion

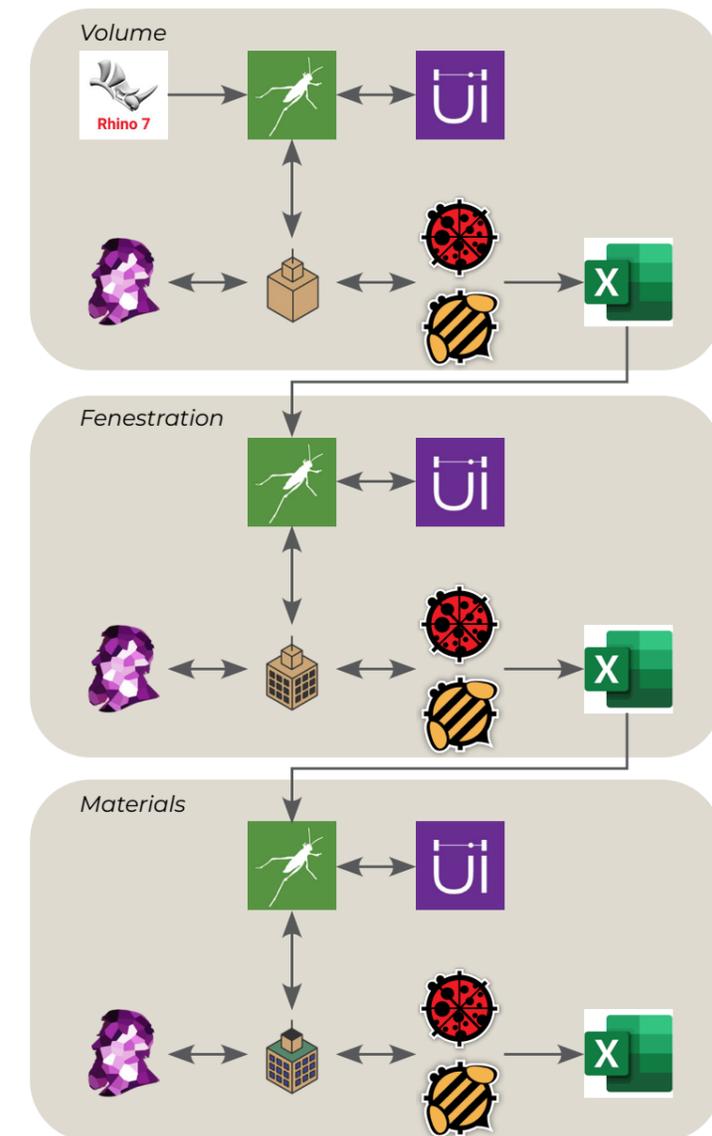


Fig 37: Simplified workflow with all stages from geometry creation to optimization

There are no limits to how many sides the geometry can have but it has to be one closed polyline and extruded as a flat surface. Having sloped roofs is possible but only if the geometry intends to remain as a single level geometry. This is because geometric growth is controlled by replicating the ground level geometry and adding the necessary levels to obtain the desired surface area.

Site Specific Information (Surveyed)

When designing for a specific location, there are some values which remain constant and should be defined prior to selecting geometry characteristics. Location and plot surface area are two factors which are not changed throughout the design process.

A plot angle was also included as a constant which refers to the degrees of rotation a plot's edge in relation to the North. This is based on the assumption a building will not be oriented East – West on a plot with a 45 degrees rotation. Instead, the building will rotate 45 degrees and be oriented either Northeast – Southwest or Northwest – Southeast.

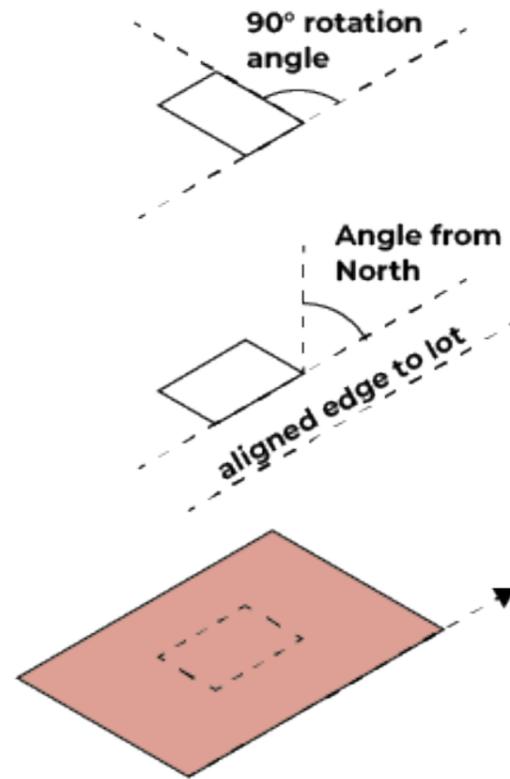


Fig 39: Example of a geometry oriented within a plot and rotation possibilities for optimization

Volume Defining Genomes

Shape Selection: Choice of predefined geometries to analyze.

Construction Area: The total construction area, considering all floors and their area. If a plot area is smaller than a desired construction area, the script will automatically create levels based on the necessary area.

Orientation: The orientation is separate from the plot angle. Orientation rotates at 90 degree intervals starting from the predefined plot angle from 0 to 270 degrees.

This was done to reduce the amount of variables added to the optimization process assuming the building will maintain its position in relation to the North but will also select the optimum position for the desired geometry.

Height: Floor to ceiling height has an impact on the geometric volume on a floor by floor scale but also on the total volume which will impact the amount of area exposed to winds and solar radiation.

Volume Fitness Objectives

- Building surface area (m²)
- Wind surface area (m²) and
- Cumulative radiation (kWh/m²).

These were chosen as volume defining passive strategies to deal with local climatic conditions. Hot climates have a larger surface area to volume ratio whilst cold climates are more compact thus, maximizing or minimizing surface area will guide the multi-objective optimization algorithm in a specific direction based on preconceived knowledge.

Surface area exposed to wind is more desirable in warmer countries or in climate type C and D countries over summer months. Determining a maximum or minimum criterion is therefore climate dependent. For cumulative radiation, colder climate types would maximize the value whilst warmer climate types minimize the value.

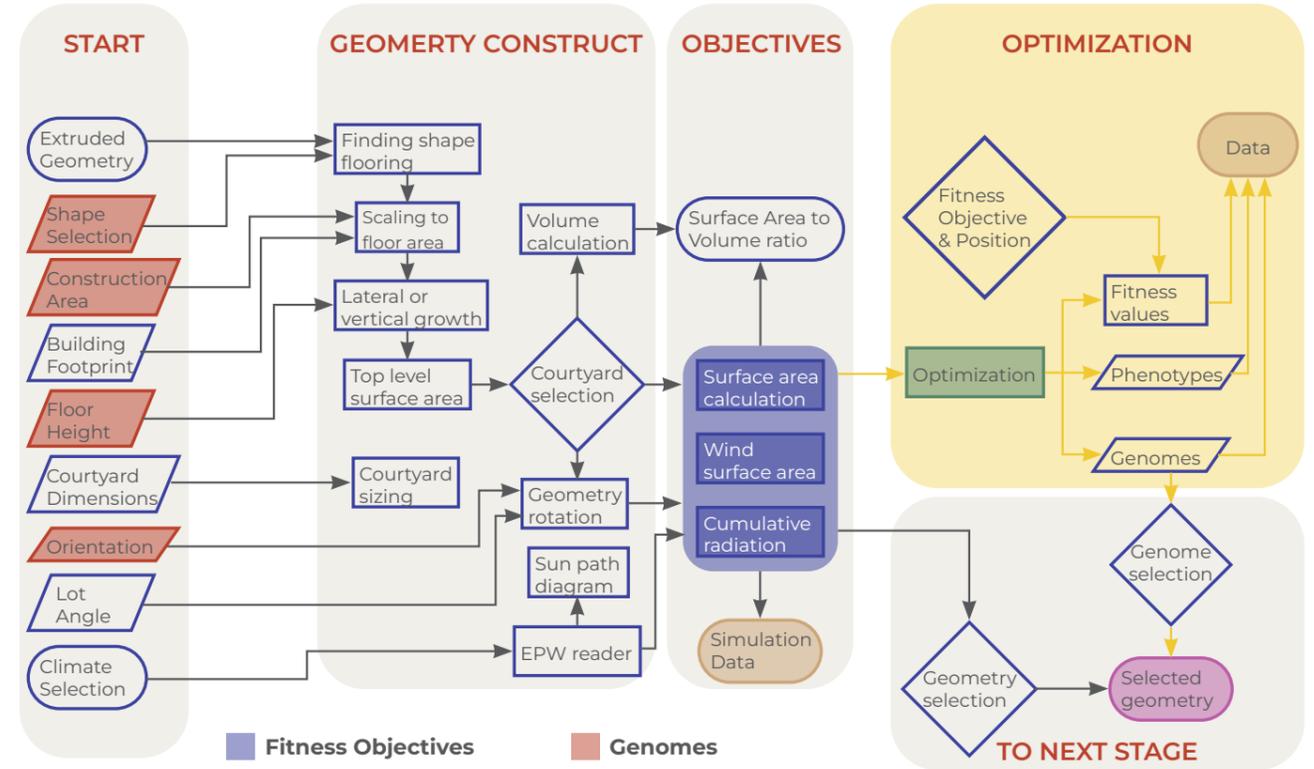


Fig 40: Volume workflow diagram

Fenestration Defining Genomes

Once the volume has been generated, it is processed through the fenestration stage where the window to wall ratio is chosen per façade. The control to define a window to wall ratio per façade is given to the user based on design priorities.

Specific views in a defined direction might be preferred over thermal comfort. If such is the case, thermal comfort can be tackled at the material stage, or a new volume might be analyzed. Window to wall ratio is used in order to maintain consistent measurements throughout various façade iterations. Furthermore, the window to wall ratio data can be used in a design development phase to quantify window sizes.

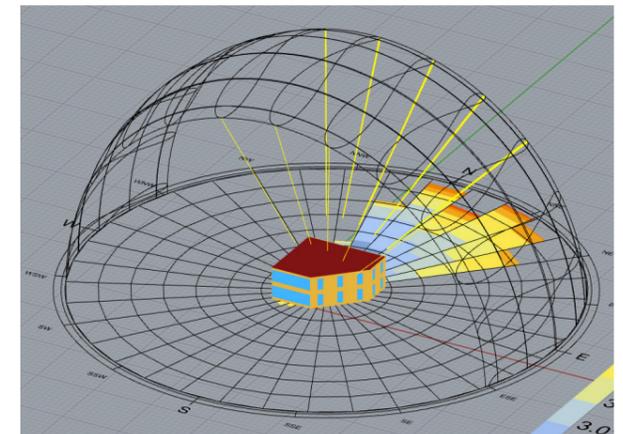
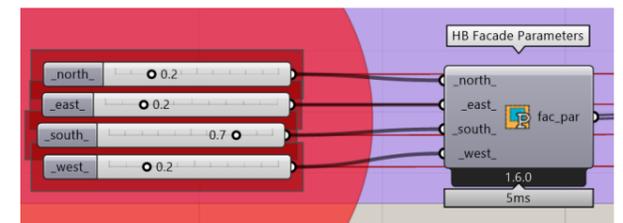


Fig 41: Fenestration choices per facade

Fenestration Fitness Objectives

The four façade window to wall ratios act as fenestration genomes whilst the fitness values focus on cooling energy (kWh), heating energy (kWh), solar gains (kWh), energy balance (kWh) and UDI as a percentage. Window size affects energy consumption, either through excess solar

gains or the lack thereof. Furthermore, UDI levels are directly correlated to window sizes in order to benefit from natural lighting, improving visual comfort and reducing the need of energy consumption for lighting.

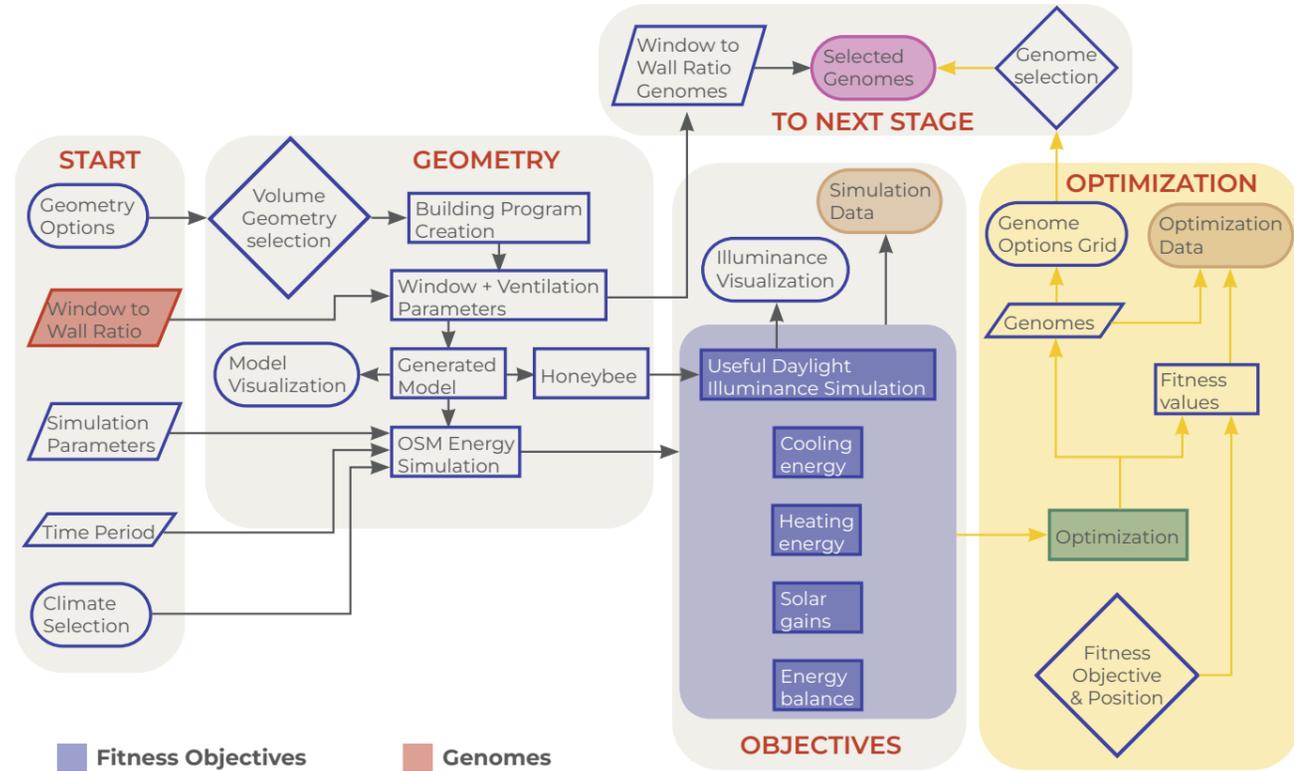


Fig 42: Fenestration workflow diagram

Material Defining Genomes

After defining window sizes, materials will play a crucial role in determining thermal comfort levels. At an early design stage, materials are still unknown, and a wall composition can have thousands of design variables. Material properties were therefore centered around element R-values and U-values. The construction was simplified into wall R-value, roof R-value, ground floor R-value, window U-value and window SHGC.

sufficient at this stage within the design process. Throughout the material selection process, it is possible to use material presets available from grasshopper's ladybug plugin or manually define the required values based on a material data sheet.

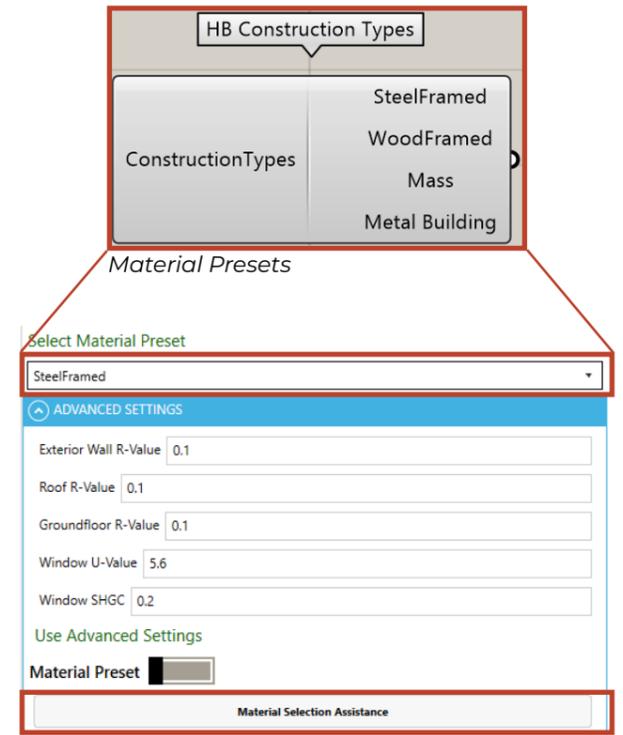
Utilizing a material data sheet as a design guide can assist in defining potential façade construction methods towards the future design development, if the exploration is not defined, presets can be selected between a steel frame, steel construction, wood construction or mass construction.

Material Fitness Objectives

Energy balance and heating and cooling energy values (kWh) are recorded to compare the results with the previous fenestration stage or other potential material genome selection. Furthermore, comfort levels are measured using two strategies; adaptive comfort and predicted mean vote (PMV) comfort levels.

Both strategies are used to compare their result variability. The adaptive comfort model assumes people are able to move places and operate windows to adjust their comfort level, meaning it calculates the comfort at different grid locations within the model. PMV considers the average comfort levels under steady state conditions, ignoring adaptability factors.

Based on the information gathered, it is possible to compare energy consumption and comfort levels at various workflow stages and between any number of simulated geometries, window to wall ratios and material properties.



Connects to excel help sheet

Fig 43: Material choice in Human UI window

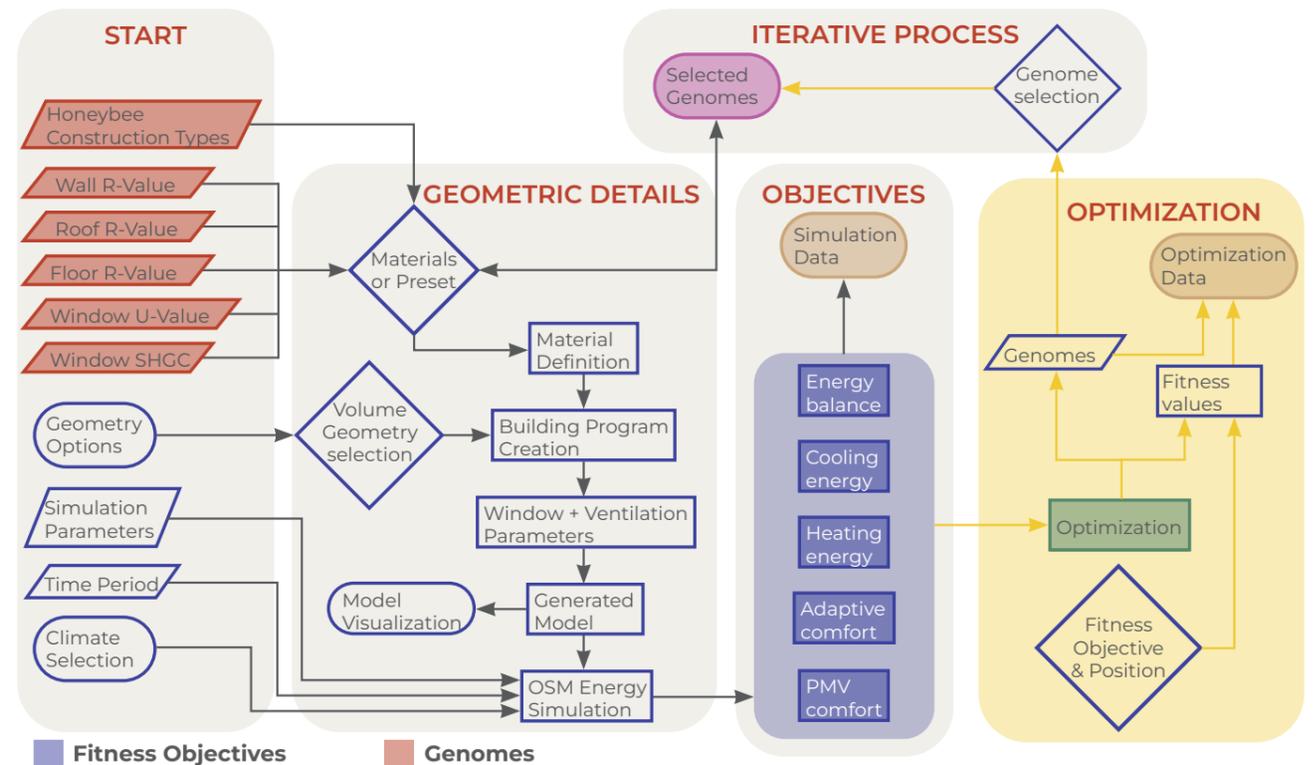


Fig 44: Material workflow diagram

Passive Strategy Defining Genomes

Finally, the potential of integrating passive design strategies can be verified by choosing to integrate roof ponds (based on climate type), sun shading devices, evaporative cooling, mass & night ventilation, internal heat capture and passive solar heating. Results are then compared with the results obtained after the material simulation, verifying if passive strategy integration for the given design within a climate type is a viable option or not.

The decision not to optimize passive strategies was based on the idea passive strategies are not dispensable building elements but additional strategies to further improve thermal comfort. Furthermore, there is a lack of control over their parameters which is useful towards an optimization workflow. Lastly, integrating passive strategies such as a trombe wall or a windcatcher develops additional construction costs which goes beyond this research topic and is something that could be discussed at later design stages rather than at a conceptual level.

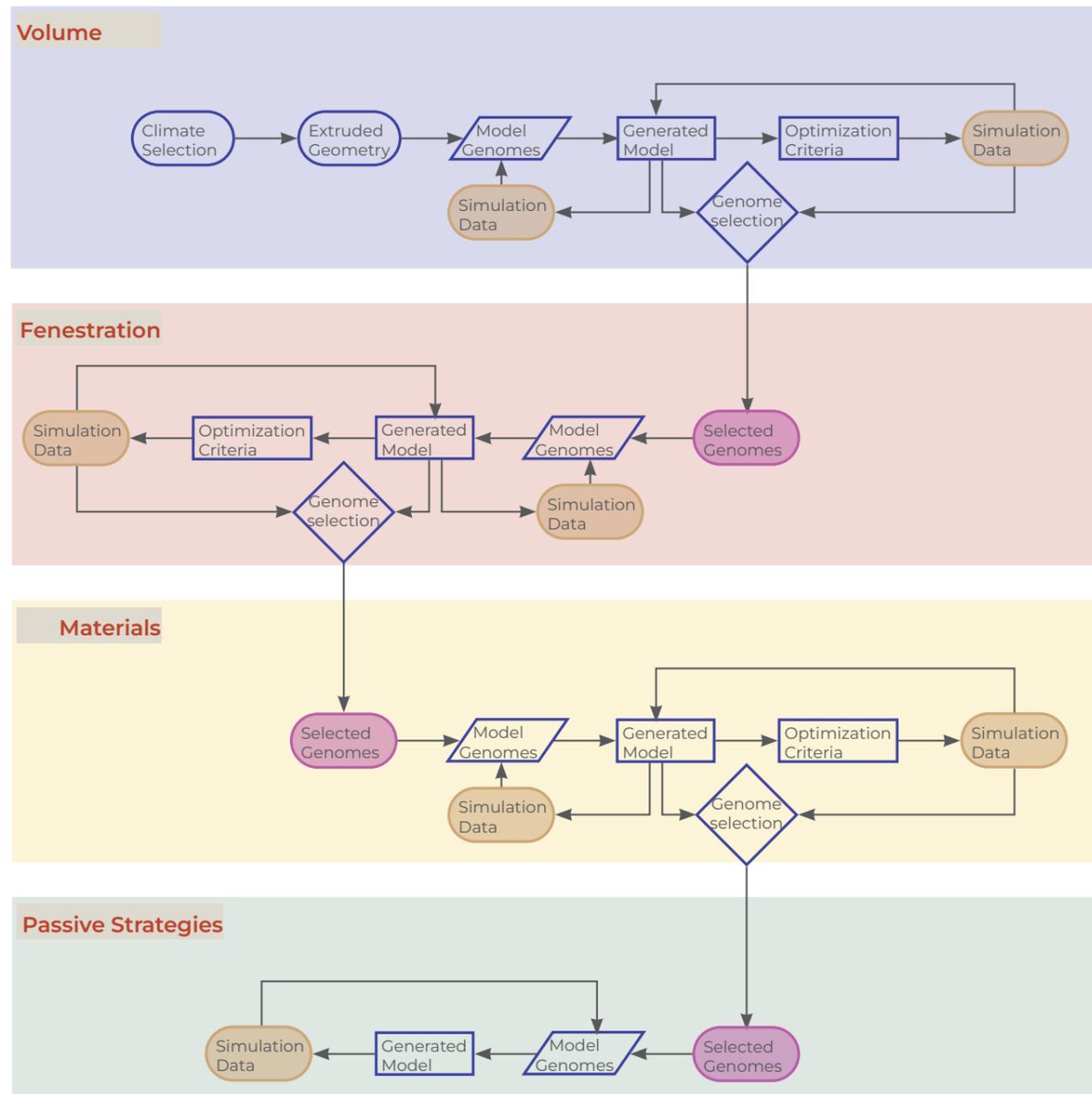


Fig 45: General workflow stepped process

3.7. Workflow Definition

Rhino's Grasshopper is used to develop the workflow for a multi-objective comparison and a multi-objective optimization process. The definition is separated into rows and columns segmenting each section into its component parts.

Rows are divided into climate selection and the stepped approach (volume, fenestration, materials and passive strategies) whilst the columns are separated into modifiers, geometry generators, simulation settings and visualizations, simulations, result recording, optimization parameters and optimization result reading.

The definition is further divided into the multi-objective comparison and multi-

objective optimization process.

Red segments belong to the development of the user interface through Human UI's Grasshopper plugin and are linked to the geometric definition through MetaHopper, a plugin which allows for a decoupled interaction between Human UI and Grasshopper workflows. Such a strategy maintains an independent process between Human UI and Grasshopper.

Weather files are EPW files obtained from Climate One Building database and each file is morphed using CCWorldWeatherGen to obtain new EPW files. Analyzing the EPW file data is done through Grasshopper in order to obtain an ASHRAE Climate Type.



Fig 46: Full Grasshopper definition separated into its component parts

Volume

The workflow centers around a basic Rhino knowledge where a 2D shape can be extruded to create a 3D geometry. The geometry (drawn in a defined layer) is imported into Grasshopper by pressing a button. Regardless of the geometric properties, the shape is scaled to a specified floor area and building height.

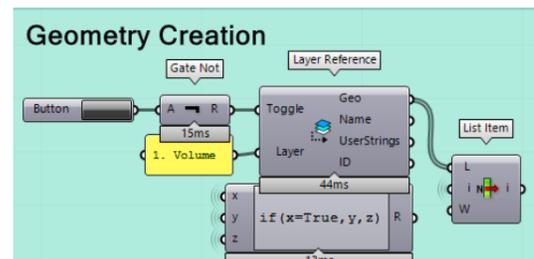


Fig 47: Geometry importing process using Lunchbox's Layer Reference component.

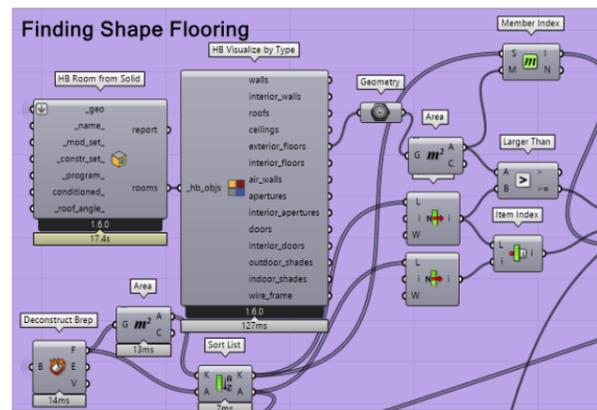


Fig 48: Floor area comparison between drawn shape and expected floor area.

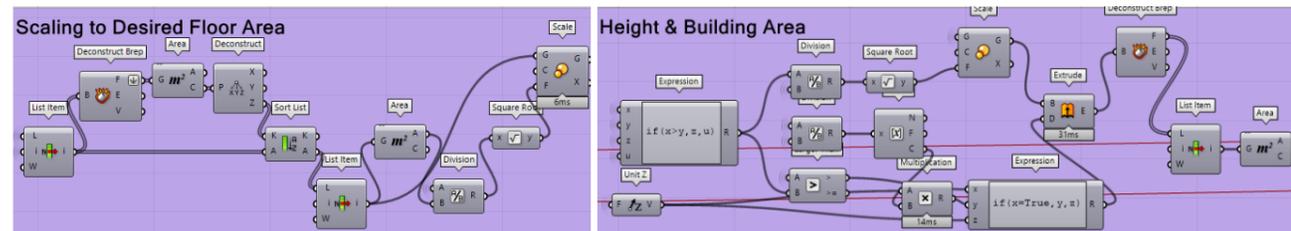


Fig 49: Geometry scaling and height adjustment process based on building footprint and construction area.

Floors are added to the geometry when floor area exceeds allowed construction area, the top floor area being equal to the difference between construction area and floor area.

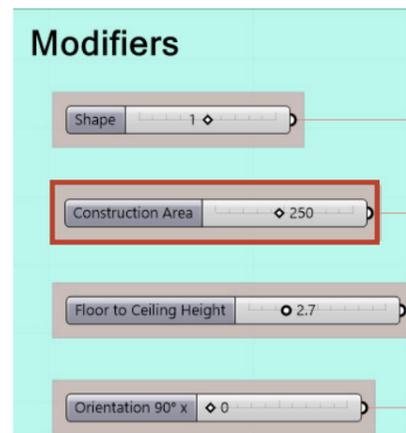
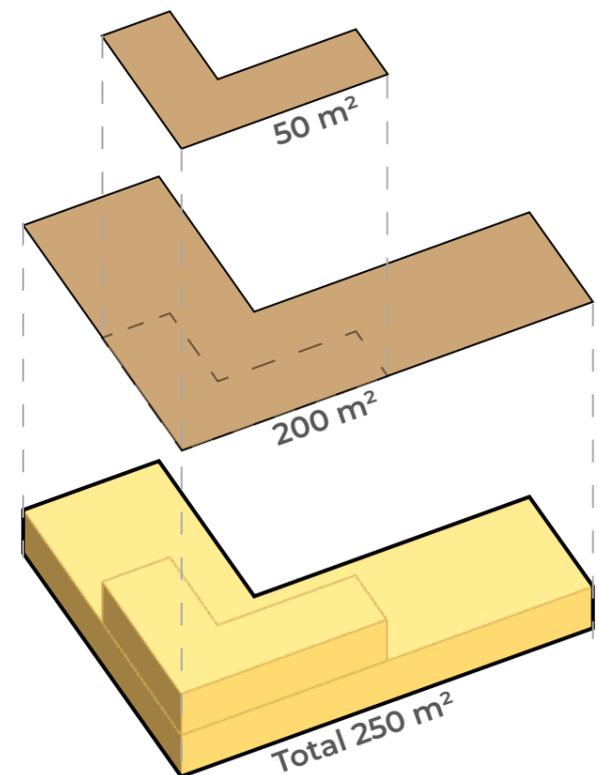


Fig 50: Geometric growth based on building footprint and construction area.



Building rotation occurs in two steps; the first rotation is defined by the plot angle at a 1 degree step (Fig. 39). The second rotation is the building's orientation within the specified plot at a 90 degree step, reducing optimization processing time.

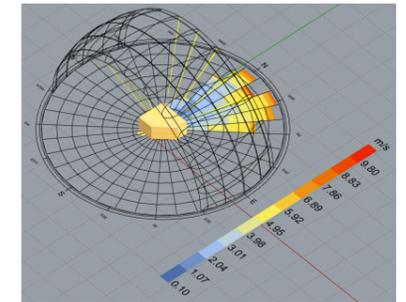
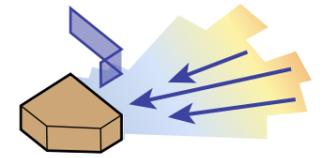


Fig 51: Exposed wind surface area schematic diagram.

Ladybug's Windrose and Sun Path components were used to have visual data about climate impacts on the selected geometry. Information from the Windrose was extracted to calculate surface area impacted by the predominant winds by using the isovist component, this surface area was used as a fitness objective.

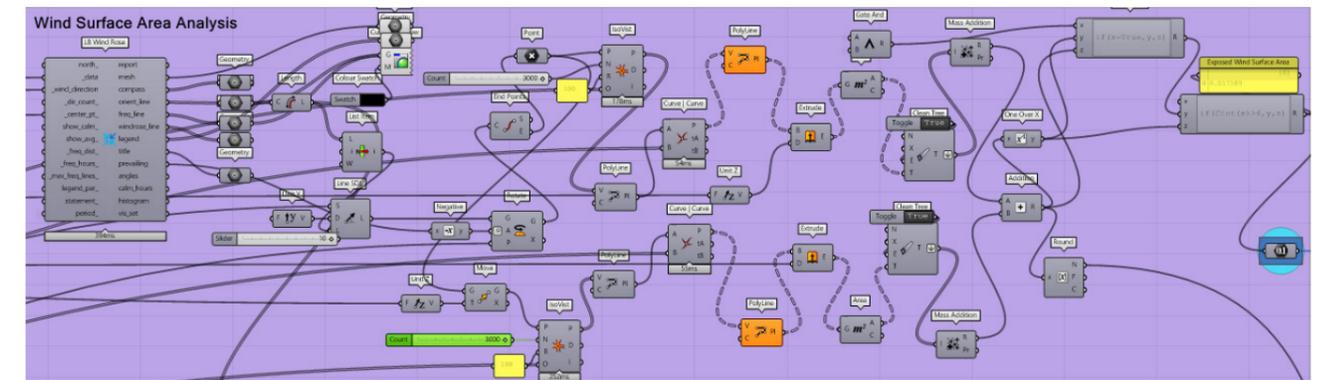


Fig 52: Exposed wind surface area Grasshopper calculation process.

Ladybug's Incident Radiation was used to obtain data for cumulative radiation, used as a second fitness objective. Finally, geometric volume and surface area were calculated to define the surface area to volume ratio.

Roof surface area was defined as the third fitness objective, defining the amount of potential space for solar panels.

All data from the simulation results is recorded into an excel spreadsheet. This occurs for each geometric iteration, adding each result one by one in order to compare results. The manual recording process is coupled with a Lunchbox plugin bake component, saving the geometry to a different layer in order to use the same geometry throughout the fenestration phase.

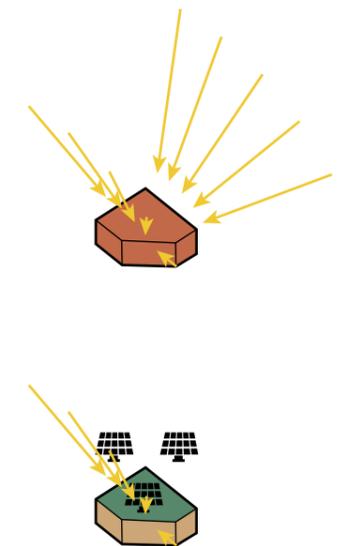


Fig 53: Incident radiation and roof surface area schematic diagram.

Fenestration

Window to wall ratio is defined per façade through ratios between 0.1 to 0.9. Single decimal places were used to reduce optimization times by eliminating small change iterations, especially during early design stages.

Simulations are carried out through HB Model to OSM to obtain room energy results for cooling energy, heating energy, solar gains and an energy balance graph. In order to visualize lighting characteristics HB Annual Daylight is used to obtain UDI results and visualization maps.

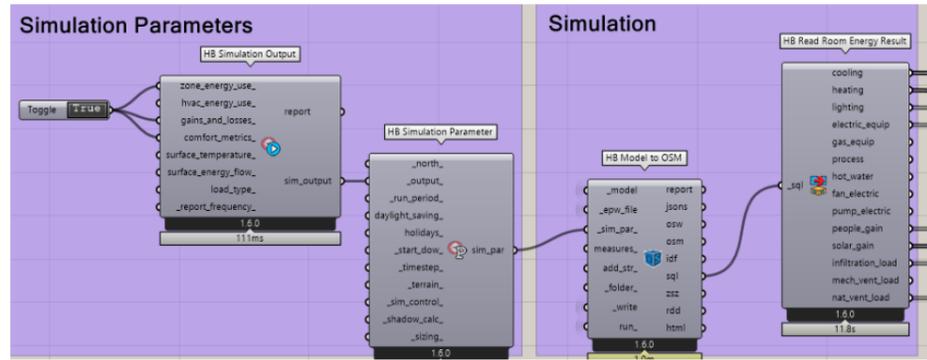


Fig 54: HB Model to OSM settings and data used for analyzing building performance.

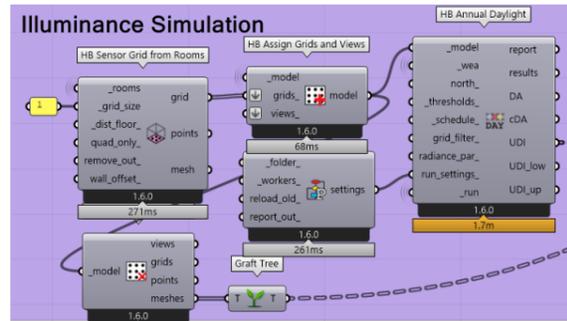


Fig 55: UDI (Useful Daylight Illuminance) settings and process.

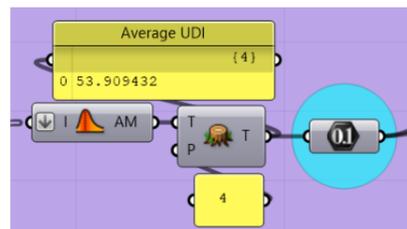
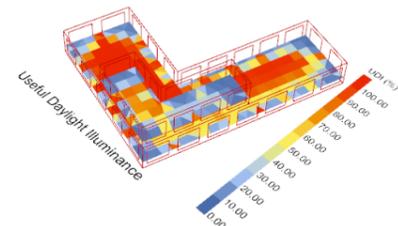


Fig 56: UDI (Useful Daylight Illuminance) numerical and visual data to be used for building analysis and performance comparison.



Numeric and graphic data indicate energy and lighting result, allowing users to compare results through visual or numerical outputs.

Data is recorded in a spreadsheet with cooling energy, heating energy, solar gains and average UDI being the fitness objectives evaluated during this design step. Window to wall ratios, being the parameters defining building functionality, are also recorded in the database. Results can be visualized and compared directly on the spreadsheet, comparing geometry, design characteristics and fitness values.

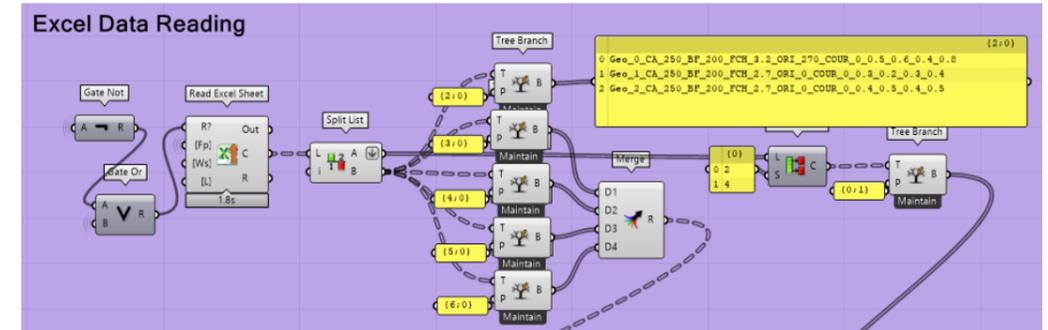


Fig 57: Data reading process in Grasshopper by extracting data from a previously recorded excel spreadsheet. Geometries in the database are shown in the top right panel.

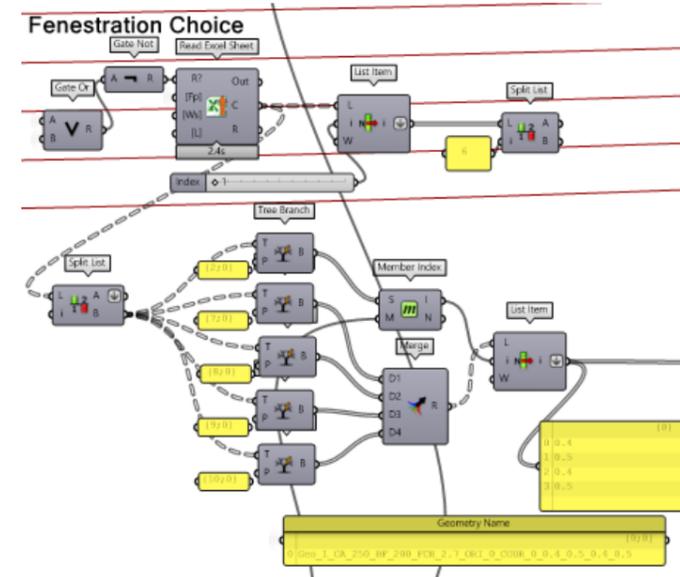


Fig 58: Fenestration genomes extracted from the excel spreadsheet recorded in the previous process' step.

In order to progress onto the next step, the spreadsheet has to be read and the genomes (window to wall ratios) are extracted to be applied into the next stage where material properties are selected.

Materials

Window properties are extracted from the previously recorded spreadsheet and used to define fenestration properties at this stage. Materials are generated either from 'no mass' components, based strictly on thermal resistance values, or from Honeybee's material preset component (Wood Frame, Mass, Steel Framed or Metal Building).

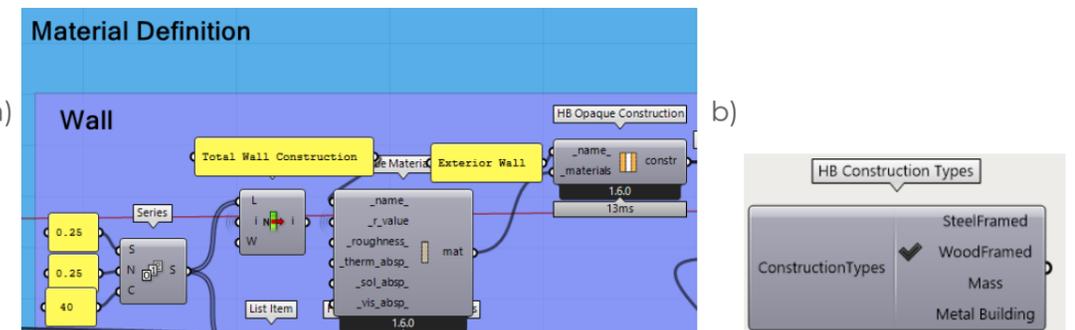


Fig 59: Material definition process through a) R-Value definition or b) Construction Types from Honeybee component.

The information is added into a construction set which defines the simulation model properties. Simulations for heating energy, cooling energy, adaptive comfort and predicted mean vote determine building objectives to reduce energy consumption and improve interior comfort.

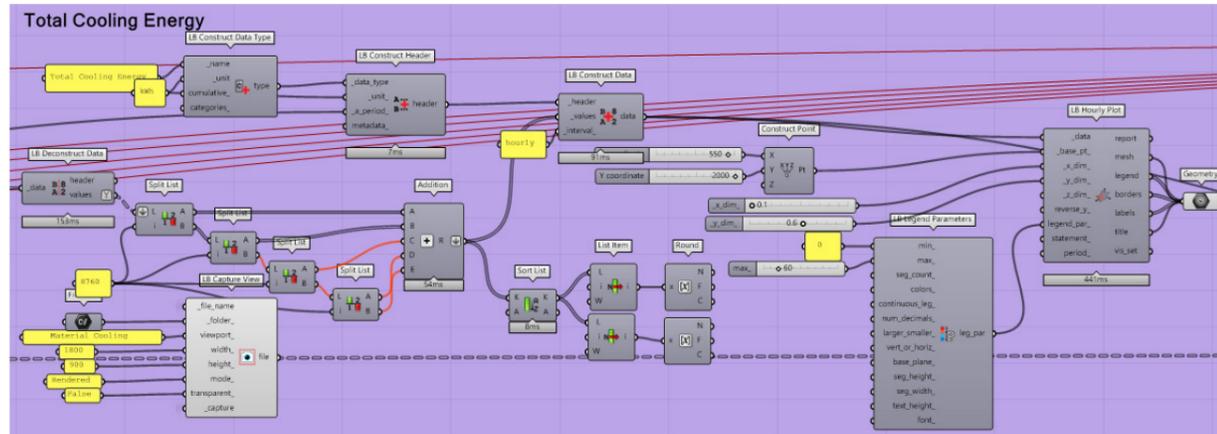


Fig 60: Obtaining annual cooling load data and graphs per floor and transforming data to an hourly basis.

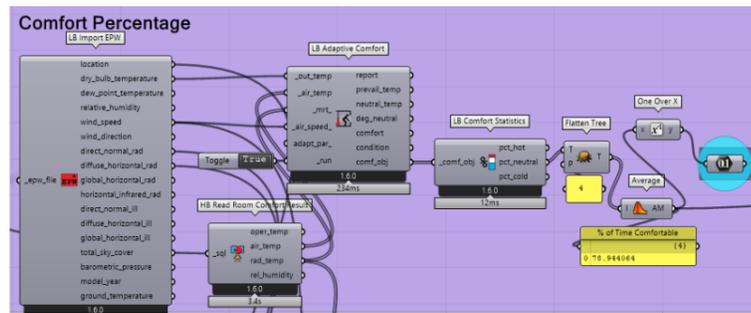


Fig 61: Calculating adaptive comfort percentage from EPW data

Energy charts in kWh (kilowatt hours) are used to compare building energy consumption between design variants on an annual basis.

Psychrometric charts are used to define comfort percentages based on mean radiant temperature and annual average wind speeds.

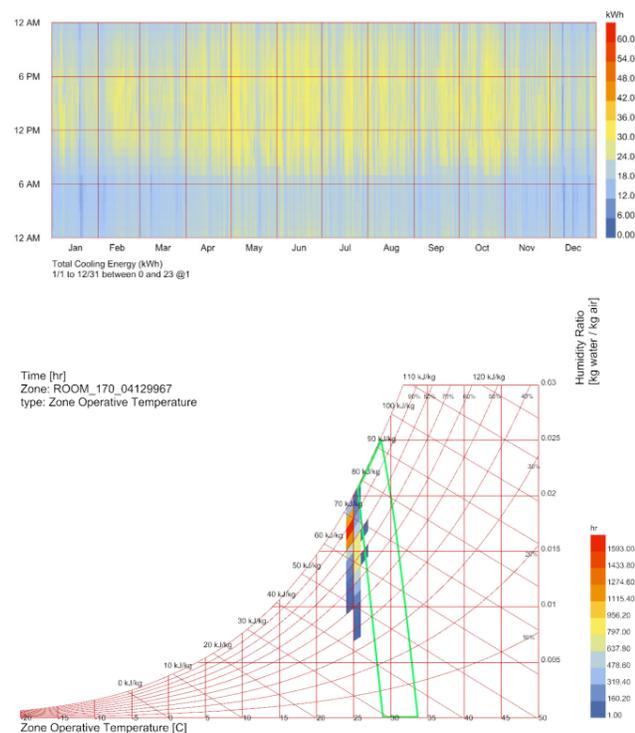


Fig 62: Graph and chart data obtained per geometric iteration and genome selection.

Data is again recorded in a spreadsheet with material thermal resistance properties and fitness objective results per simulated iteration. Results obtained at this stage are compared to determine the solution fitting design priorities.

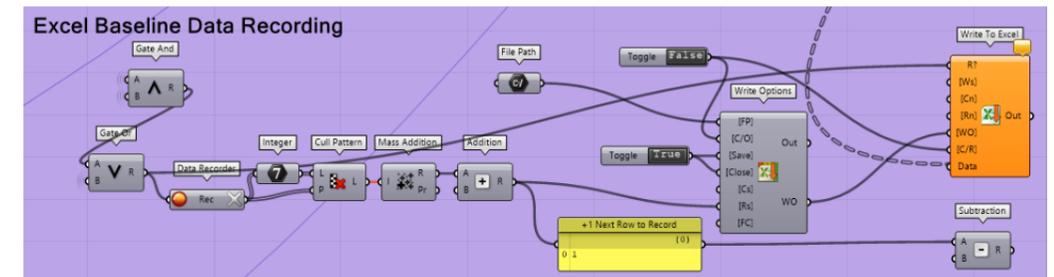


Fig 63: Excel recording process for various data iterations per project.

| NAME | COOLING ENERGY | PMV COMFORT % | ADAPTIVE COMFORT % | HEATING ENERGY |
|--|----------------|---------------|--------------------|----------------|
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0_0.3_0 | 59566.76 | 0.00 | 77.09 | 0.00 |
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0_0.4_0 | 57832.52 | 0.22 | 76.03 | 0.00 |
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0_0.4_0 | 67869.40 | 0.08 | 87.53 | 0.00 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0_0.3_0 | 76739.47 | 0.00 | 95.33 | 0.00 |

| WALL R-VALUE | ROOF R-VALUE | GROUND R-VALUE | WINDOW U-VALUE | SHGC |
|--------------|--------------|----------------|----------------|------|
| 2.00 | 6.62 | 0.33 | 2.86 | 0.23 |
| 2.00 | 6.62 | 0.33 | 2.86 | 0.23 |
| 0.45 | 3.76 | 0.33 | 2.86 | 0.23 |
| 0.45 | 3.76 | 0.33 | 2.86 | 0.23 |

Fig 64: Excel spreadsheet data recording per geometric iteration with fitness values and genomes recorded.

Passive Strategies

Using the same model generated at a material level, passive strategies can be added to impact the design's energy consumption and interior comfort. Activating the roof pond setting will adjust the roof's thermal resistance according to values found throughout the literature research.

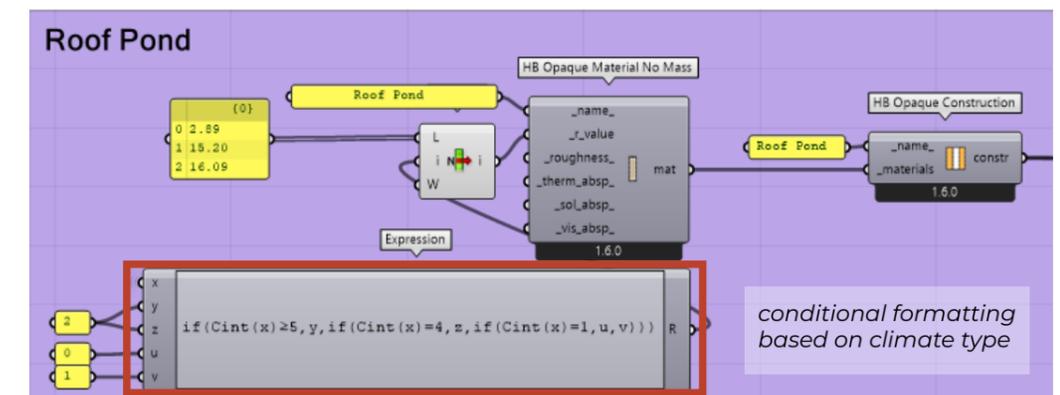


Fig 65: Roof pond property definition based on climate type according to the literature research described in in Table 7.

Sun shading will generate a sun shading system, adjustable through Grasshopper only, which allows between a regular sun shading or a mashrabiya. Both these strategies impact energy consumption.

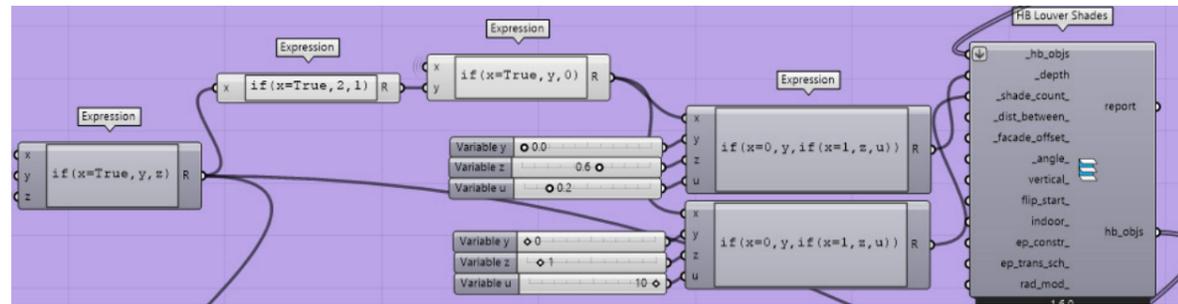


Fig 66: Shading system definition based on climate type. Shading parameters can be modified on a project by project basis through Grasshopper sliders.

The remaining strategies (Evaporative Cooling, Mass + Night Ventilation, Internal Heat Capture and Passive Solar Heating) are introduced through Ladybug's Passive Strategy component.

Ladybug strategies have an impact on internal comfort levels but will not impact energy consumption results.

A new psychrometric chart is generated showing the comfort areas based on the implemented passive strategies. The comfort percentage can be used to compare passive strategy impact.

Data from these last simulations is recorded in a fourth spreadsheet with the fitness values and the implemented strategies being integrated. Results can then be compared with results obtained at the material step to see the impact passive strategy implementation can have on a building.

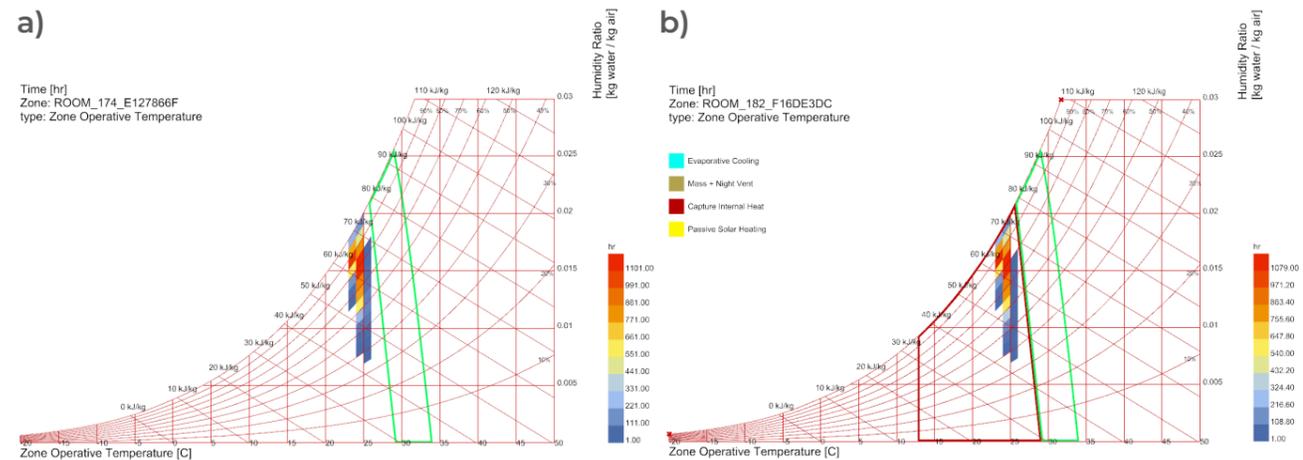


Fig 67: Psychrometric chart comparison at a) Material process stage and b) After integrating passive strategies.

Human UI

Human UI allows for the development of a user interface using Grasshopper components and can be accessed through a toggle button in the Grasshopper canvas.

Every workflow step (volume, fenestration, materials and passive strategies) is integrated into Human UI, accessible through tabs in the user interface. The design process using the user interface is exactly the same as the one using Grasshopper, Human UI being the front-end and Grasshopper serving as the back end.



Fig 68: Early stage design optimization user interface tab selection to guide the design process created using Human UI through Grasshopper.

Throughout the interface sliders and drop-down menus allow geometry to be modified and settings to be adjusted based on user preference. Building data and fitness objectives are shown on the left which can serve to inform specific design changes needed.

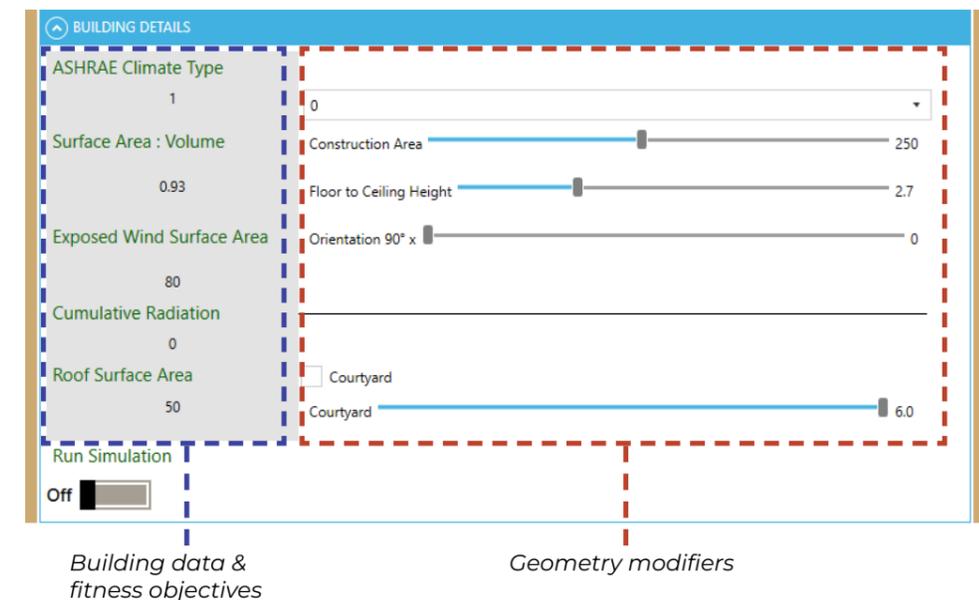


Fig 69: Early stage design optimization user interface showing building data and genome selection, generated using Human UI plug-in through Grasshopper.

Desired values can be saved in order to return to specific or preferred design alternatives, a compilation of these settings can be stored, their results analyzed one after another by 'Restore State' commands whilst the simulation toggle is 'On'.



Fig 70: State saving mechanics to save genome selection and restore states based on designer preferences and ease of comparison.

Any results desired to be saved can be recorded in the database by pressing the 'Record in Database' button. These results are then extracted and used for the next step in the design workflow.

The steps are similar throughout the whole process with genomes, building data and fitness objectives being shown every step of the way. Comparison charts are further used when number comparisons are required, having a visual queue to performance metrics between design choices.

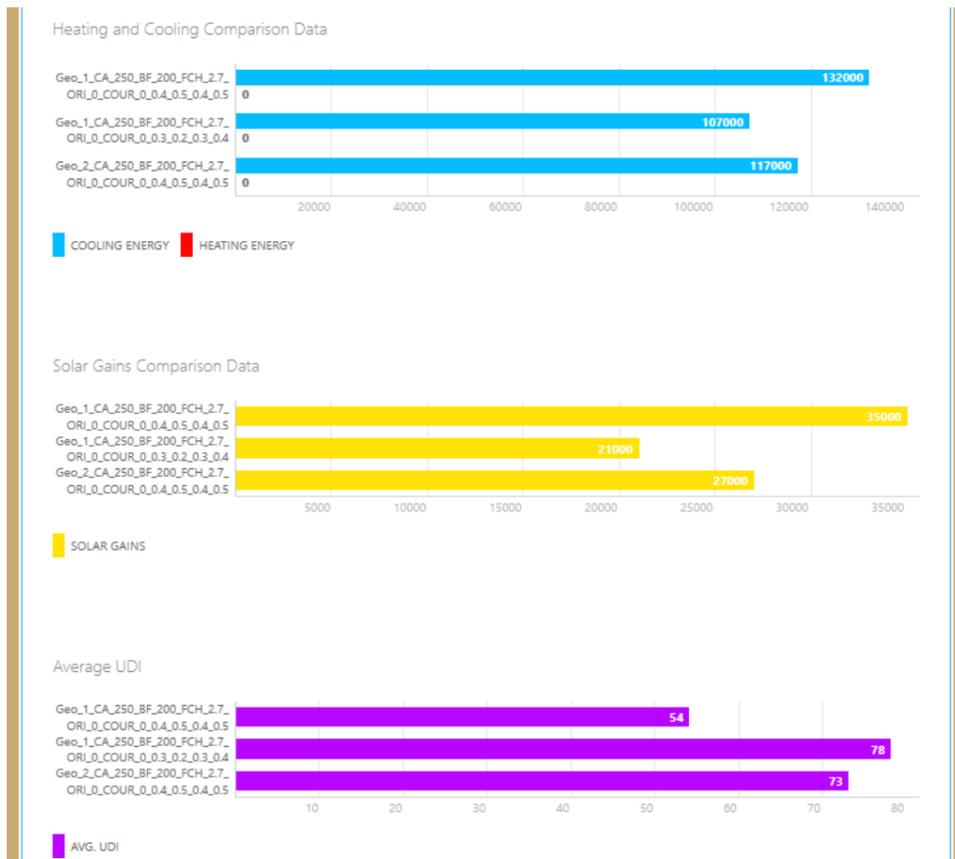


Fig 71: Data comparison charts visible in the early stage design optimization user interface based on geometric iteration.

Further comparative data is available in the form of graphs where annual heating and cooling loads are shown in kWh's (kilowatt hours) on a yearly basis to compare when consumption spikes occur. UDI (useful daylight illuminance) and psychrometric charts are also presented within the decision making process to compare design interior comfort levels.

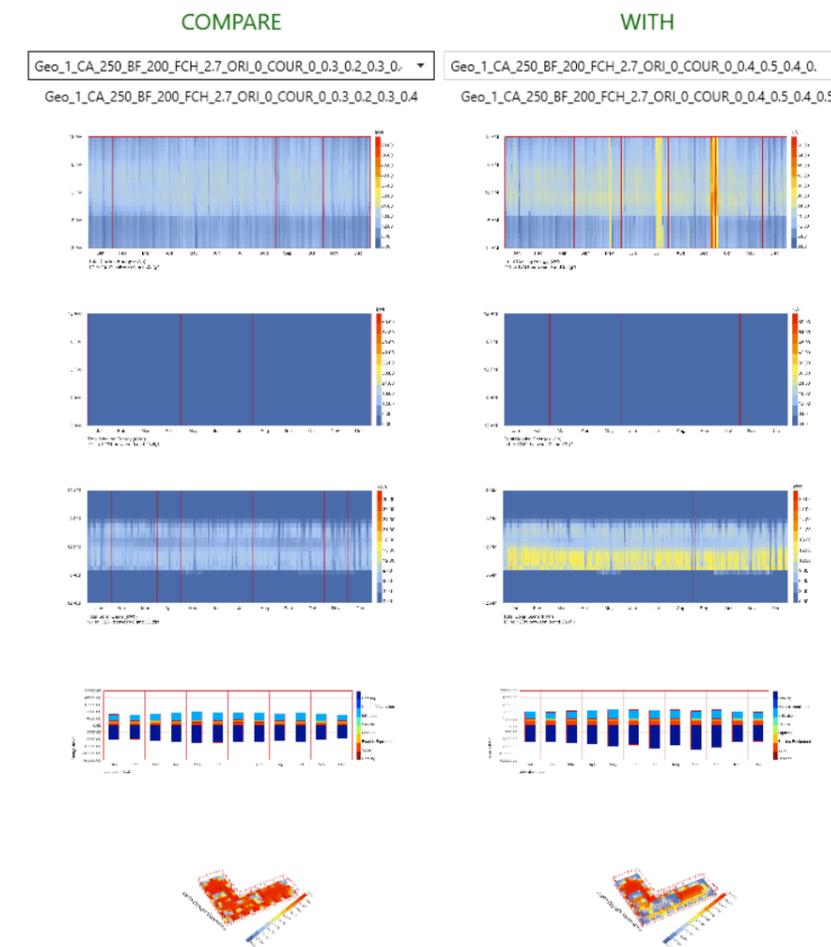


Fig 72: Data comparison graphs accessible through the user interface as a means of gathering more data towards design decisions.

The final step in the user interface is a 1 to 1 result comparison between design alternatives. Selecting a design to compare and a design to compare with the comparative results are shown in absolute numbers and percentages to show either design improvement or deterioration.

| Compare | | |
|---|--------------------------|--------------------|
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.4.0.5_0.4.0.5_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SF | | |
| With | | |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.3.0.2_0.3.0.4_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_C | | |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.3.0.2_0.3.0.4_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23_RP_Mass+NightVent_CaptureInternalHeat_PassiveSolarHeating | | |
| Material Results | Passive Strategy Results | Result Difference |
| Cooling Load | Cooling Load | Cooling Load |
| 58000 | 77000 | 19000 (28%) |
| PMV Comfort % | PMV Comfort % | PMV Comfort % |
| 0 | 100 | 100% |
| Adaptive Comfort % | Adaptive Comfort % | Adaptive Comfort % |
| 76 | 95 | 19% |
| Heating Load | Heating Load | Heating Load |
| 0 | 0 | 0 (0%) |

Fig 73: Final data comparison between two design iterations, having the final energy consumption metrics and comfort levels and their difference in absolute numbers and percentages.

Volume
User-Interface



Fig 74: Volume tab in the designed user interface.

Fenestration
User-Interface

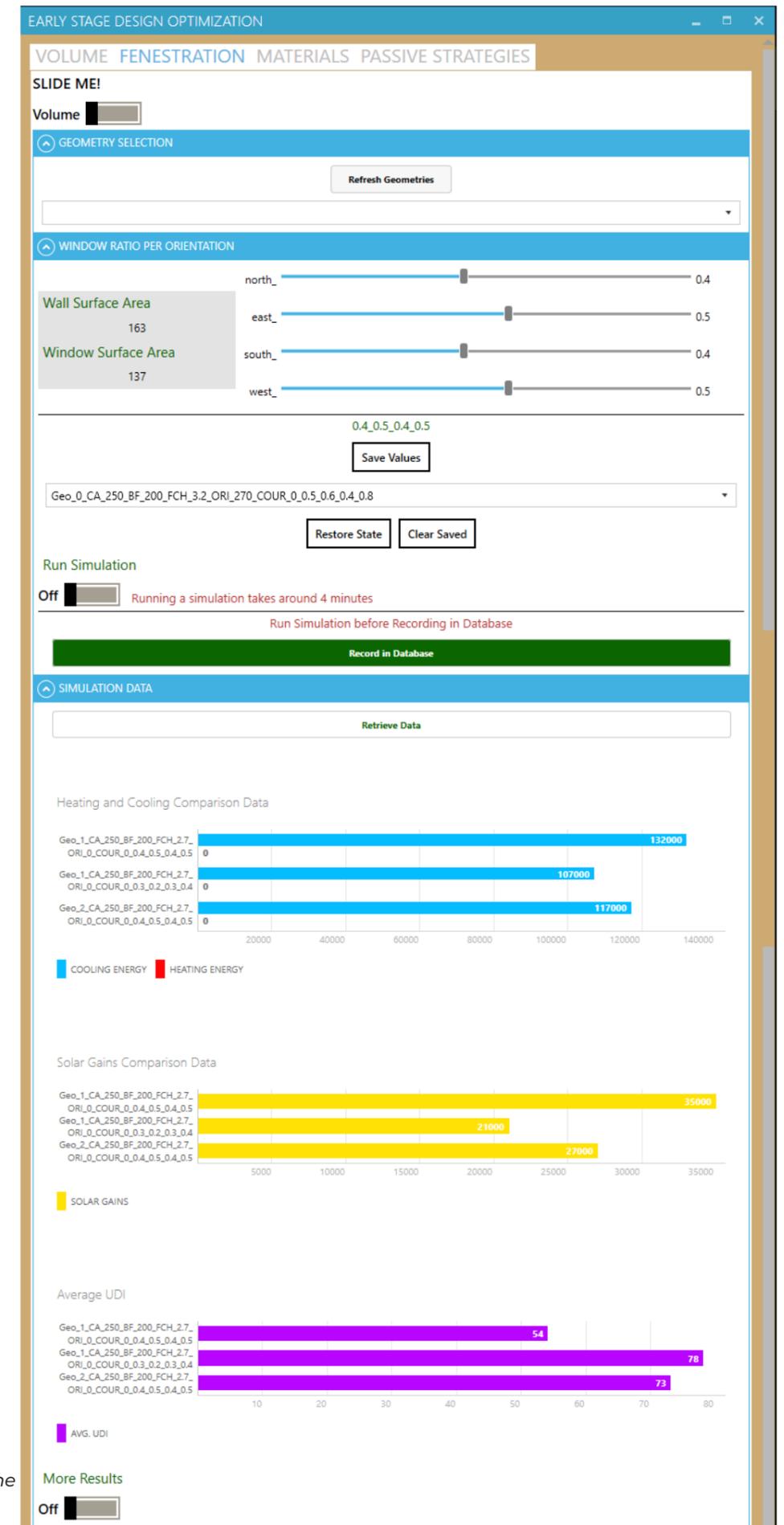


Fig 75: Fenestration tab in the designed user interface.

EARLY STAGE DESIGN OPTIMIZATION

VOLUME FENESTRATION MATERIALS PASSIVE STRATEGIES

SLIDE ME!

Fenestration

GEOMETRY SELECTION

Refresh Geometries

MATERIAL SELECTION

Wall R-Value: 1.466956

Roof R-Value: 3.757746

Ground Floor R-Value: 0.332726

Window U-Value: 2.857274

Window SHGC: 0.23

Cooling Load: 69731.18186

PMV Comfort %: 0.479452

Adaptive Comfort %: 78.944064

Heating Load: 0

Select Material Preset: SteelFramed

ADVANCED SETTINGS

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_SteelFramed_W_1.47_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23

Save Values

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SF

Restore State Clear Saved

Run Simulation

Off

Run Simulation before Recording in Database

Record in Database

SIMULATION DATA

Retrieve Data

Cooling and Heating Energy Comparison

| Scenario | Cooling Energy | Heating Energy |
|--|----------------|----------------|
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 59600 | 0 |
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 57800 | 0 |
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23 | 67900 | 0 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23 | 76700 | 0 |

Thermal Comfort Percentages

| Scenario | PMV Comfort % | Adaptive Comfort % |
|--|---------------|--------------------|
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 77 | 76 |
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 76 | 76 |
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23 | 88 | 88 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23 | 95 | 95 |

More Results

Off

Fig 76: Material tab in the designed user interface.

EARLY STAGE DESIGN OPTIMIZATION

VOLUME FENESTRATION MATERIALS PASSIVE STRATEGIES

GEOMETRY SELECTION

_2019_ClimateZone1_SteelFramed_W_1.47_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23

Restore State

PASSIVE STRATEGY SELECTION

Roof Pond

Roof Pond

Roof ponds are mainly used for cooling during hot summer periods, being able to reduce the interior's average temperature by acting as thermal mass and by improving night-time ventilation through evaporative cooling.

Sun Shading

Sun Shading

Solar shading excludes undesired solar radiation from entering the living space. Window shutters can help with heat retention throughout the night, avoiding heat losses.

Evaporative Cooling

Evaporative Cooling

Water is evaporated and passes from a liquid to a gas. This transition requires energy, which is extracted from the air in the form of heat. As a result of this process, the air is cooled down.

Mass + Night Ventilation

Mass + Night Ventilation

Night flushing works by opening up pathways for wind ventilation and stack ventilation throughout the night, to cool down the thermal mass in a building by convection.

Capture Internal Heat

Capture Internal Heat

People, lighting and appliances generate heat. This component assumes the building is free-running and people are able to operate windows to avoid excess heat.

Passive Solar Heating

Passive Solar Heating

The polygon represents the conditions under which sun-exposed thermal mass can keep occupants warm in winter. Temperatures can get as high as 12 C above the max temperature of the comfort polygon.

Run Simulation

Off

Run Simulation before Recording in Database

Record in Database

DATA COMPARISON

Retrieve Data

Compare

Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SF

Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 With

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_C

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass+NightVent_CaptureInternalHeat_PassiveSolarHeating

| Material Results | Passive Strategy Results | Result Difference |
|------------------------|--------------------------|---------------------------|
| Cooling Load: 58000 | Cooling Load: 77000 | Cooling Load: 19000 (28%) |
| PMV Comfort %: 0 | PMV Comfort %: 100 | PMV Comfort %: 100% |
| Adaptive Comfort %: 76 | Adaptive Comfort %: 95 | Adaptive Comfort %: 19% |
| Heating Load: 0 | Heating Load: 0 | Heating Load: 0 (0%) |

Passive Design Strategy Options

Cooling and Heating Energy Comparison

| Scenario | Cooling Energy | Heating Energy |
|---|----------------|----------------|
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 58000 | 0 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 59600 | 0 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass+NightVent_CaptureInternalHeat_PassiveSolarHeating | 76700 | 0 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass+NightVent_CaptureInternalHeat_PassiveSolarHeating | 75700 | 0 |

Thermal Comfort Percentages

| Scenario | PMV Comfort % | Adaptive Comfort % |
|---|---------------|--------------------|
| Geo_2_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.4.0.5.0.4.0.5_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 76 | 76 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SHGC_0.23 | 77 | 76 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass+NightVent_CaptureInternalHeat_PassiveSolarHeating | 100 | 95 |
| Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass+NightVent_CaptureInternalHeat_PassiveSolarHeating | 100 | 95 |

PMV Comfort Psychometric Chart

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_WoodFramed_W_2_R_6.62_F_0.33_Win_U_2.86_SF

Geo_1_CA_250_BF_200_FCH_2.7_ORI_0_COUR_0.0.3.0.2.0.3.0.4_2019_ClimateZone1_Mass_W_0.45_R_3.76_F_0.33_Win_U_2.86_SHGC_0.23_Mass+NightVent_CaptureInternalHeat_PassiveSolarHeating

Time [hr]
Zone: ROOM_84_63A67E55
type: Zone Operative Temperature

Humidity Ratio [kg water / kg air]

Zone Operative Temperature [C]

Fig 77: Passive Strategy tab in the designed user interface.

3.8. Computational Assisted Design

Workflow priorities focused on the ability to provide users with information to guide the design process. Guiding the design process was considered more valuable than just informing about a singular best result. The ability to compare and contrast various design options takes into account both qualitative and quantitative data towards a design choice.

Throughout the process, usually a dialogue between a client (user) and an architect, the workflow functions as an engineering support tool to define scenarios. Providing users with freedom to design strengthens the collaborative process, defines design priorities and improves user knowledge on design performance.

Having a wider array of information at early design stages will assist in the future development of the design; having a basis of what is expected as a design geometry and what can be expected during performance.

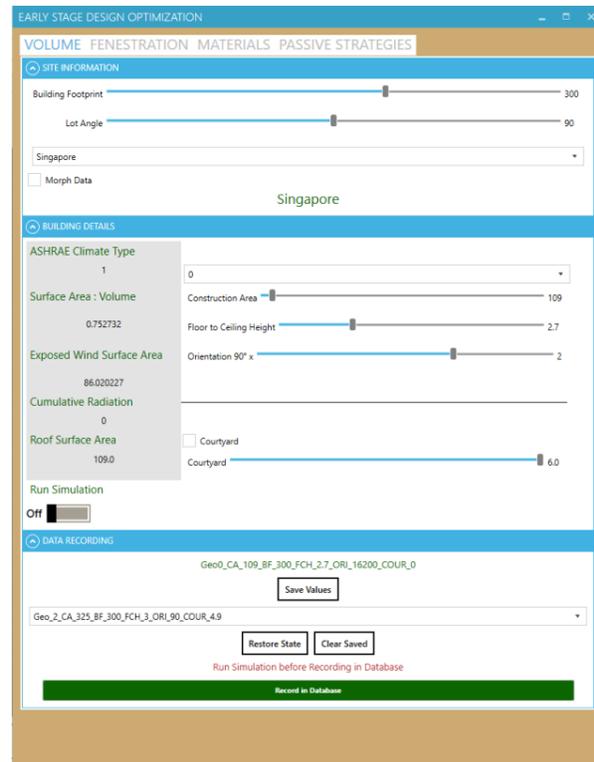


Fig 78: User interface page full page layout.

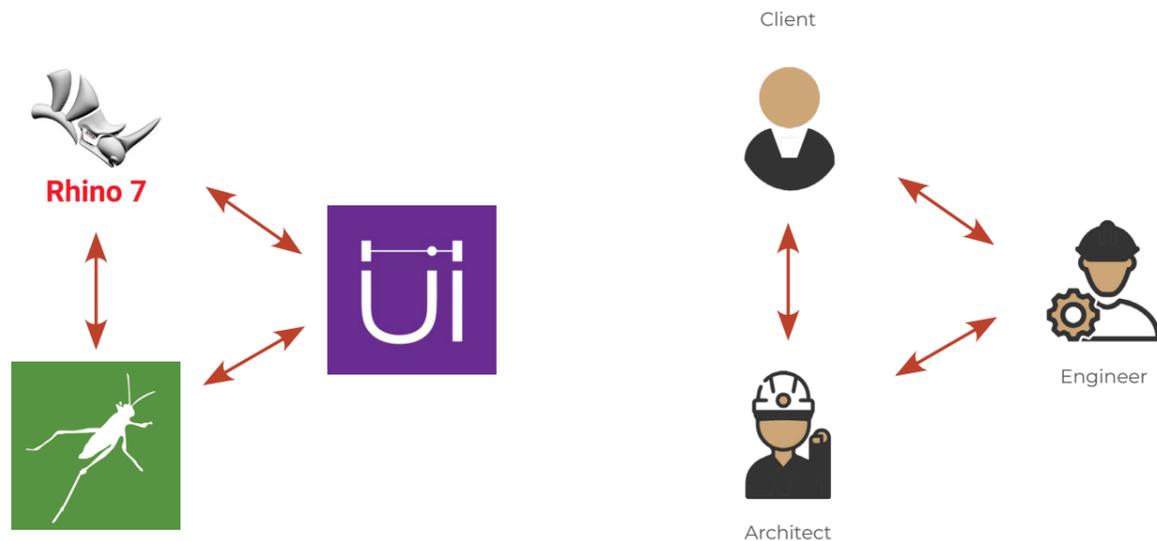


Fig 79: Communication interaction between design programs to develop a methodology as a comparison to building teams and their interaction towards completing design projects.

The proposed tool does not intend to substitute any design stage during the design process. Instead, it intends to integrate into the repertoire of tools available as a pathway to determine energy consumption and interior comfort levels.

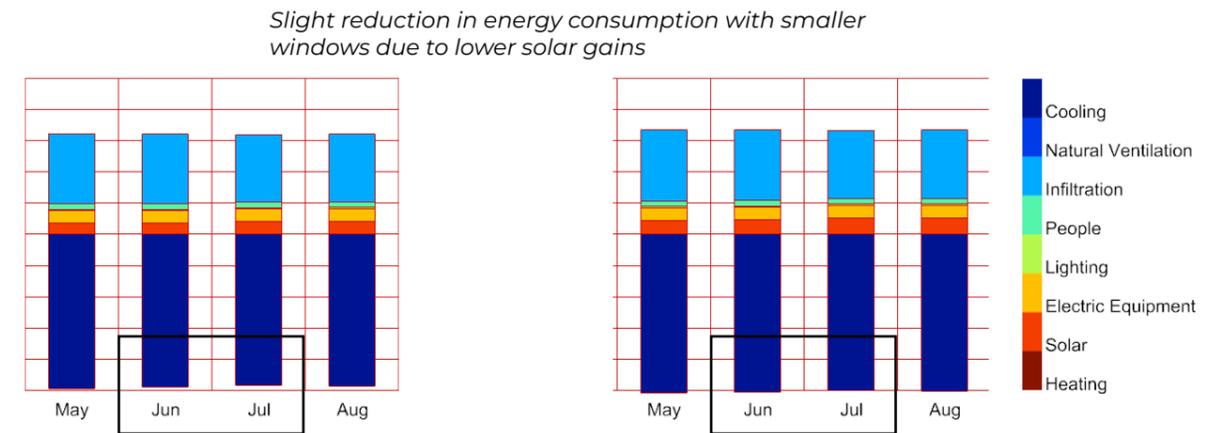
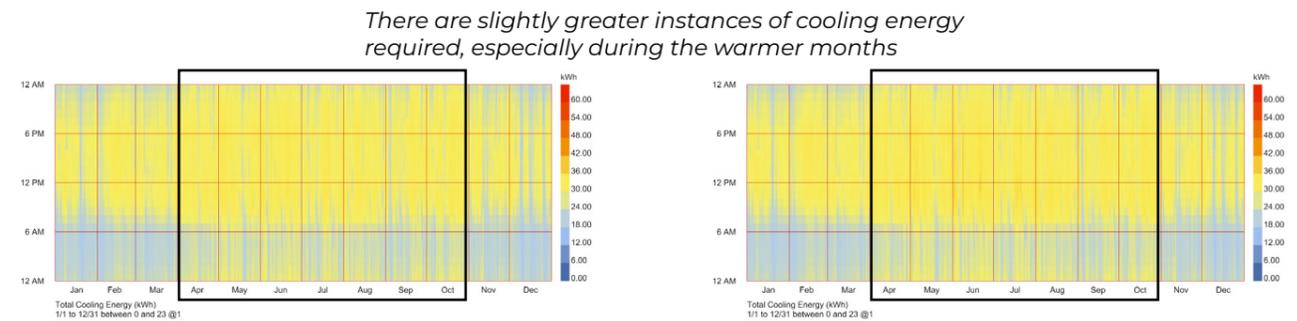
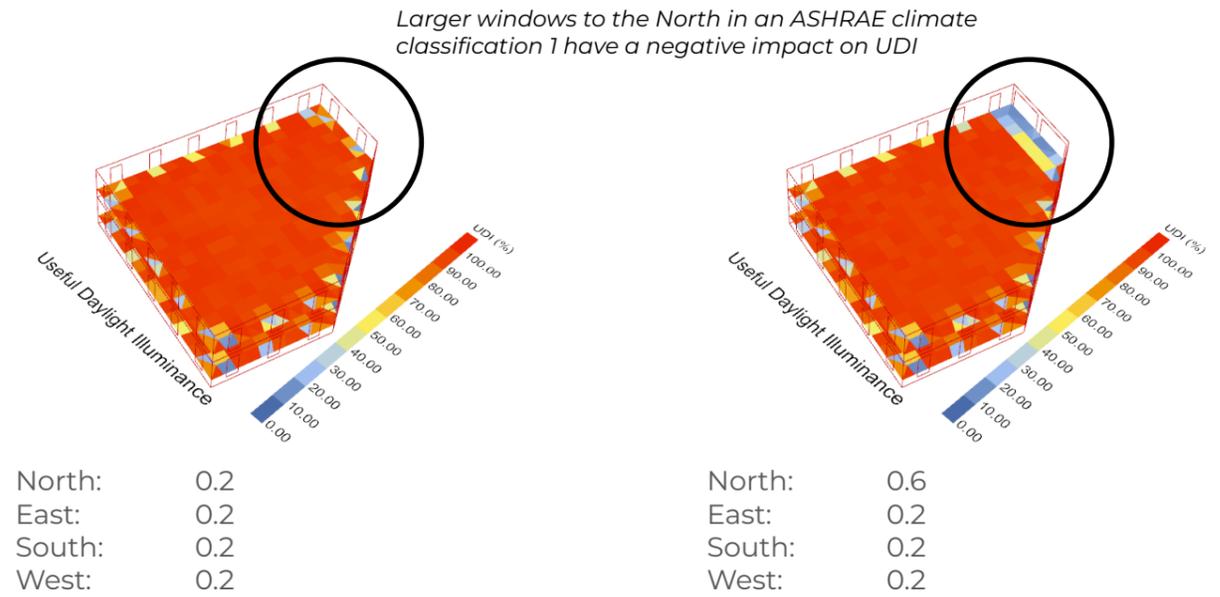


Fig 80: Data gathering process towards design development, building a relationship between design modifications and their impact on performance.

Knowledge acquired during the design process and throughout the various workflow stages will be used to improve on the current design. Integrating climate during the early design stages reinforces the focus on developing a climate-responsive design, taking into account local conditions having an impact on the built environment. Weather patterns heavily influence a building's energy consumption and comfort levels, being aware of the impacts will facilitate design decisions at later design stages.

OPTIMIZATION AS A DESIGN PROCESS

4.1. Integrating Optimization Workflows into the Design Process

4.2. Architectural Design Process

4.3. Computational Disruption in the Design Process

4.4. Data as a Design Guide

4.5. Impact of Optimization on the Design Process

4.1. Integrating Optimization Workflows into the Design Process

An architectural design process is the method by which architects explore and identify design characteristics to achieve a successful architectural outcome (Hettithanthri, 2022). Sequential stages of a design process identify a problem and develop towards project implementation that will become a solution to the initial problem.

Architectural Design Workflows

Asimow developed a model in 1962, dividing the process into stages: Primary needs, feasibility study, preliminary design, detailed design, planning for production, planning for distribution, consumption planning and project delivery (Abowardah, 2016). The Royal Institute of British Architecture (RIBA) divided the process into four stages and 12 steps: Briefing (Inception & Feasibility Study), Sketch Planning (Outline Proposals & Scheme Design), Working Drawing (Detailed Design, Production of Information, Bill of Quantities & Tender Action) and Site Operation (Project Planning, Operation on Site, Completion & Feedback) (RIBA, 1967).

Integrating optimization workflows into the design process has been done at various design stages, mainly during late design stages such as consumption planning or site operation from Asimow's and RIBA's workflows respectively.

Optimization as Process

Optimization models are optional design components which can enrich the design process through data driven design approach, responding to new requirements towards net zero buildings established by the European Green Deal directives.

Users and architects are not expected to become experts on technical formulations regarding energy modeling or fully comprehend the methodology behind such calculations. Nevertheless,

understanding the relationship between design factors impacting a building's operations are necessary to build a relationship between design and consequence.

Optimization tools have the benefit of offering information about a building's operations based on a building's properties and characteristics. Furthermore, if correctly integrated and utilized into a design process, optimization tools serve as learning procedures between cause and effect for a building's design parameters.

Throughout the design stages, the project's energy consumption is improved but also knowledge and insight are retained to be used in a future project's decision making process.

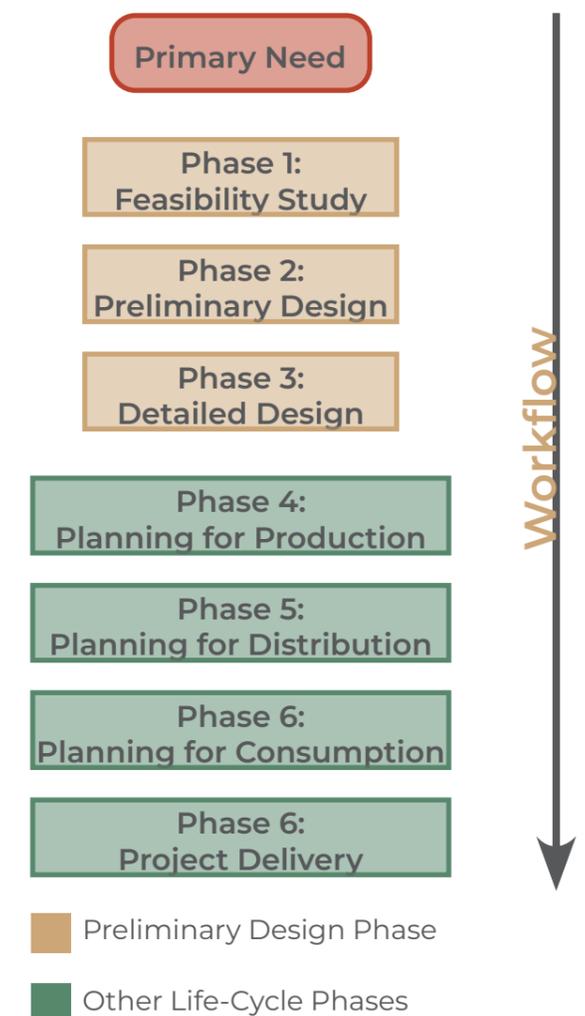


Fig 81: Design Workflow: Asimow's (1962)

4.2. Architectural Design Process

Design processes are not set, they are not manuals which have to be followed, they are guidelines to organize a project towards an effective delivery. Adapting over time and based on new regulations, RIBA published an updated plan of work in 2020. The new plan of work considers sustainability aspects and couples the design process with Building Information Modelling (BIM).

RIBA's plan of work (2020) separates into 8 stages:

Early Design

0 – Strategic Definition

Defines client requirements, assesses project risk and project budget. At this stage, knowledge acquired from past projects is considered towards project planning.

1 – Preparation / Briefing

Brief is developed including dimensions, project and sustainability goals are defined. A project budget is agreed and site information is presented.

2 – Concept Design

Architectural concept with engineering requirements is prepared according to project requirements. Design reviews are carried out with clients and stakeholders.

Design Development

3 – Spatial Coordination

Design studies and engineering analysis aligning to architecture spatial concept. Cost, strategies and specifications are updated.

4 – Technical Design

Technical designs for architecture and engineering, building system information is generated in order to construct the building.

| Stage | # | RIBA | # | ACE |
|--------------|---|----------------------|-----|--------------------|
| Pre-Design | 0 | Strategic Definition | 0 | Initiative |
| | 1 | Preparation & Brief | 1 | Initiation |
| Design | 2 | Concept Design | 2.1 | Concept Design |
| | | NOT USED | 2.2 | Preliminary Design |
| | 3 | Developed Design | 2.3 | Developed Design |
| | 4 | Technical Design | 2.4 | Detailed Design |
| Construction | 5 | Construction | 3 | Construction |
| Handover | 6 | Handover & Close-Out | | NOT USED |
| In Use | 7 | In Use | 4 | Building Use |
| End of Life | | NOT USED | 5 | End of Life |

Fig 82: RIBA's 2020 Plan of Work and Architect's Council of Europe Stage Comparisson

Design Construction

5 – Manufacturing and Construction

All logistics are developed such as site and construction program. Building manual is generated, serving to verify construction quality and operation.

Design Operations

6 – Handover

Project is delivered to the client and a review of project performance begins. Building contract finishes.

7 – Use

Post occupancy performance evaluation continues during building use. Project outcomes and sustainability goals are verified with the ones proposed in stage 1.

Serving as a project guide, RIBA's plan of work stages are purposefully vague which allows for the adaptation on a project to project basis. During the early stages, strategic definition and preparation / briefing, the process focuses on planning, with little to no designing until the conceptual design stage.

During the preparation / briefing stage sustainability goals are defined. These goals should be measurable and site specific, drawing from opportunities and constraints present for and within the current project.

Sustainability goals develop based on national and local policies. Furthermore, project sustainability objectives can be set based on past knowledge obtained from the post evaluation feedback from previous projects carried out during stage 7 from RIBA's plan of work.

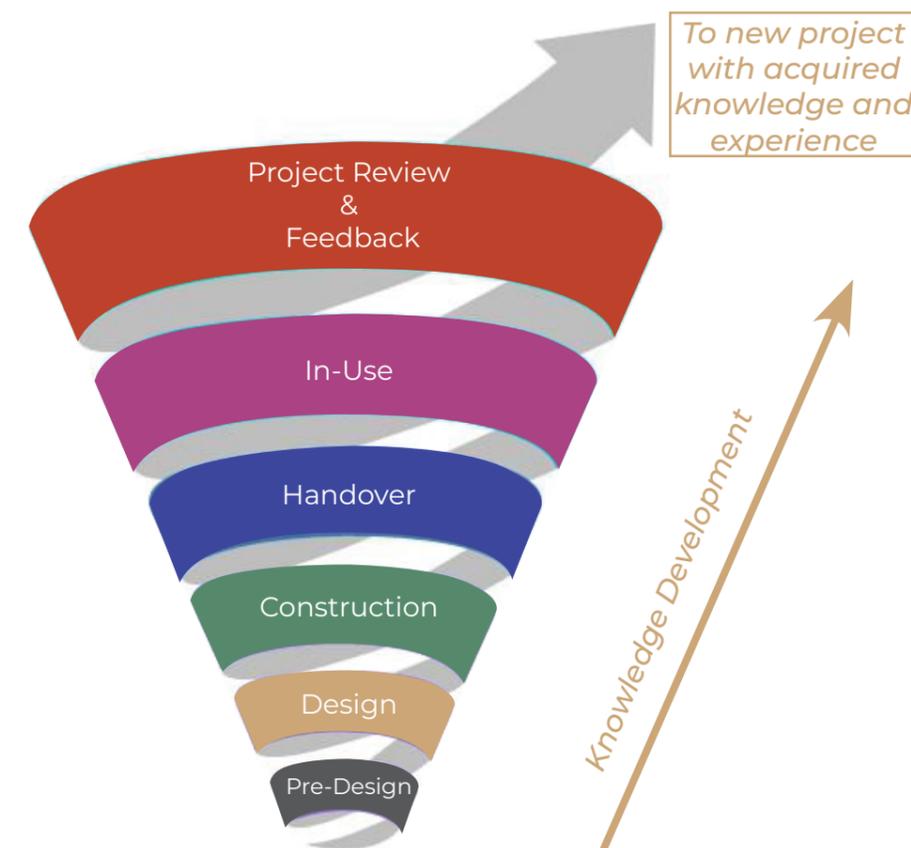


Fig 83: Schematic process for RIBA's 2020 Plan of Work Feedback Loop for future projects

4.3. Computational Disruption in the Design Process

The proposed multi-objective optimization workflow focuses on reducing energy consumption and improving interior comfort levels through climate responsive design. The process provides numerical data at different design stages which can be site specific and fall within project requirements and constraints.

Quantitative data obtained from the workflow can serve in the definition for project sustainability goals, having a project baseline which is climate specific. Generating data from simple geometric extrusions offers the possibility of exploring a variety of design possibilities which satisfy spatial requirements and concepts.

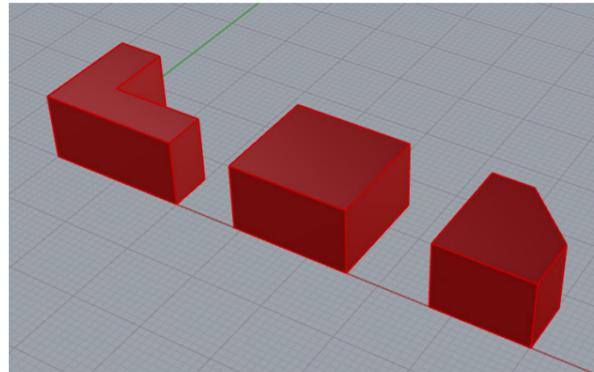


Fig 84: Geometric extrusions used during the simulation process

Workflow Integration Stage 1 - Preparation & Briefing

A multi-objective workflow (comparison and optimization) would benefit the design process at the early design stages, information generated from the workflow's exploration would benefit setting the sustainability goals during stage 1 – Preparation / Briefing. Site constraints such as dimensions, locations and angle (relative to the North) will define building positioning and orientation.

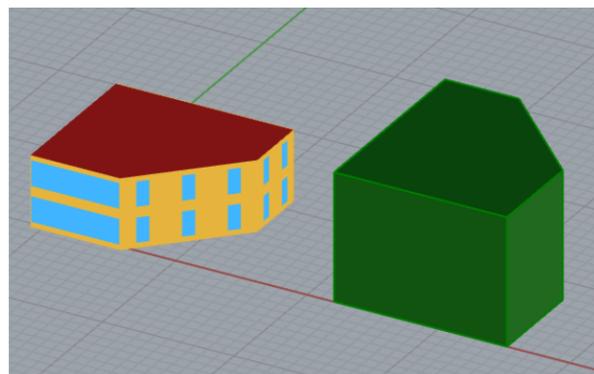


Fig 85: Geometric transformation from initial drawings

Workflow Integration Stage 2 - Concept Design

Including the multi-objective workflow after stage 2 – Concept Design will guide initial concept geometry explorations and getting formal design reviews from project stakeholders. Clients are encouraged to take part during the exploration phase to strengthen design priorities and feedback through collaborative design.

With this information as basis, the multi-objective workflow can assess different geometric variants and their requirements in order to reduce energy consumption and improve interior comfort.

A list of potential passive design strategies can also be noted that could further reduce energy consumption. Building upon the knowledge through a site specific approach at early design stages has the potential to define with greater clarity a project's sustainability goals and design priorities.

Climate and Geometric Scenario Exploration

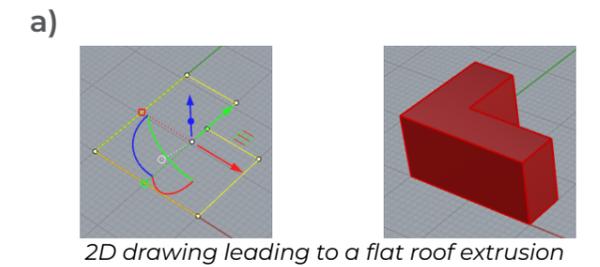
Integrating a multi-objective workflow into the design process builds upon the architect's knowledge acquired from other projects but it also focuses on site specific constraints and climate. The ability of constructing upon morphed climate data can further build comparative studies between current and future climate expectations having an impact on the built environment. The workflow invites clients and stakeholders to take part in the design process, following the trade-offs at each design stage. Through the design exploration phase, design decisions are not final but open a conversation towards user design priorities.

Geometric exploration is simplified into flat roof shapes with limited possibility of customizing geometries, especially multi-story buildings. Although the explorations are used to generate ideas, the ability to only draw 2D shapes can stifle creativity.

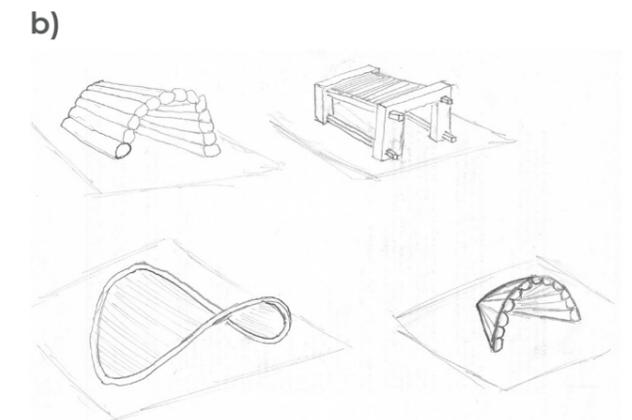
This can have an impact into a strong architectural concept as forms are explored prior to design concept. There is a duality between concepts developing from the forms explored or whether geometry develops from.

Result Evaluation

The workflow generates data through various stages which can serve to define sustainability goals. However, simulation results can't be defined as highly accurate due to the simplistic simulation characteristics. Misinterpreting simulation results as operative targets is misleading, so a proper problem formulation and realistic sustainability goals have to be set as project constraints. Simulation results are ideal to build comparisons, but their numerical value should not be expected during operation.



2D drawing leading to a flat roof extrusion

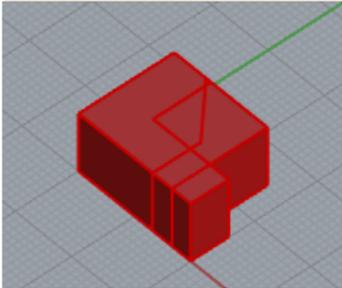


several sketched explorations in seconds

Fig 86: Comparison between conceptual geometry generation a) Proposed Workflow b) Architectural Exploration through sketching

Grasshopper Input and Output Workflow

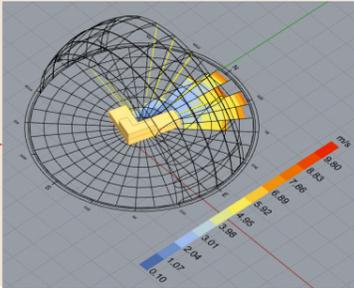
Input 1
Drawn geometry



Process 1
Geometry modification components and climate analysis



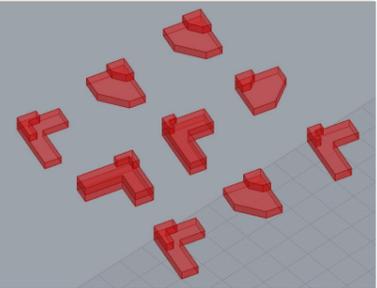
Output 1.1
Adjusted geometry



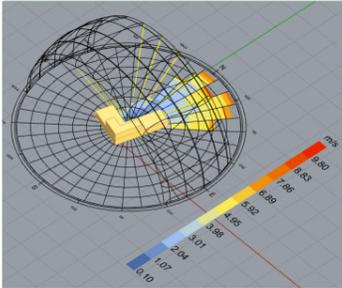
Optimization 1
Geometry optimization



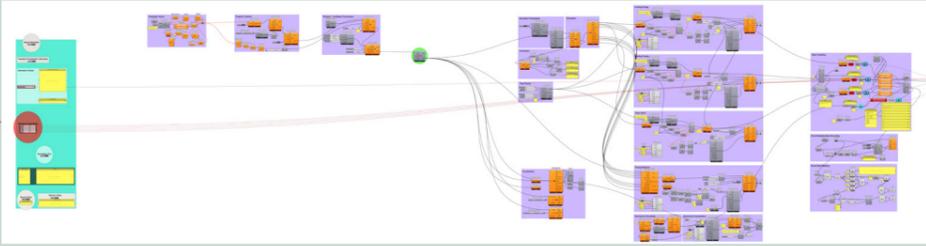
Output 1.2
Volume optimization grid



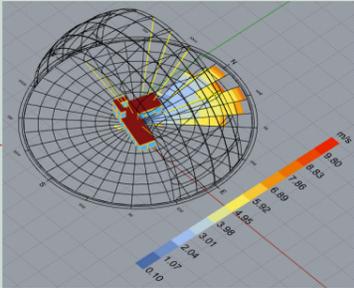
Input 2
Output 1.1 is used



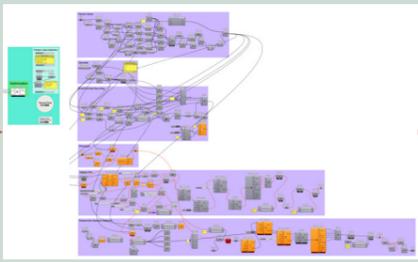
Process 2
Fenestration choice per facade (window to wall ratio)



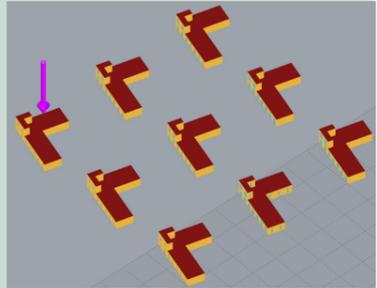
Output 2.1
Geometry with windows



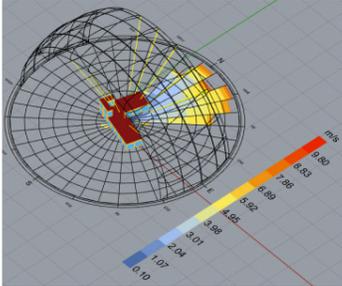
Optimization 2
Fenestration optimization



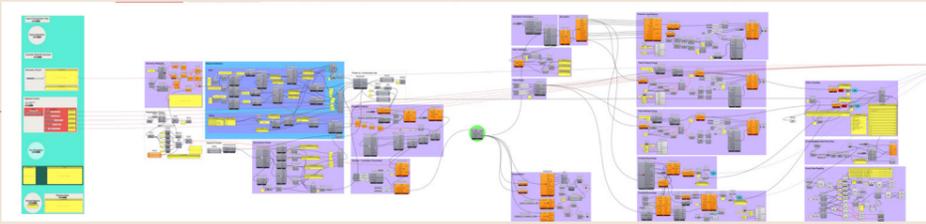
Output 2.2
Window optimization grid



Input 3
Output 2.1 is used



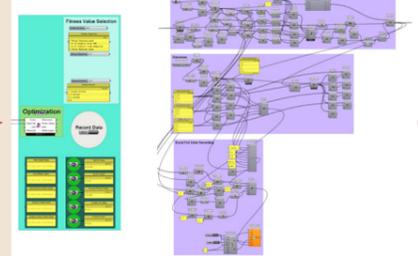
Process 3
Selection of shell R-values or building presets



Output 3.1
Energy consumption and comfort data

| Column Names | |
|------------------------|----------------|
| 0 Climate Type | 0 1 |
| 1 Name | 1 Geo_1_CA_219 |
| 2 Cooling Energy | 2 51730.585839 |
| 3 PMV Comfort % | 3 0 |
| 4 Adaptive Comfort % | 4 75.941781 |
| 5 Heating Energy | 5 0 |
| 6 Wall R-Value | 6 2 |
| 7 Roof R-Value | 7 6.62 |
| 8 Ground Floor R-Value | 8 0.33 |
| 9 Window R-Value | 9 2.86 |
| 10 SHGC | 10 0.23 |

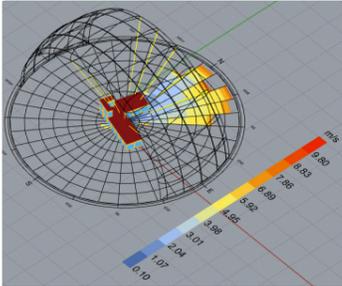
Optimization 3
Thermal resistance optimization



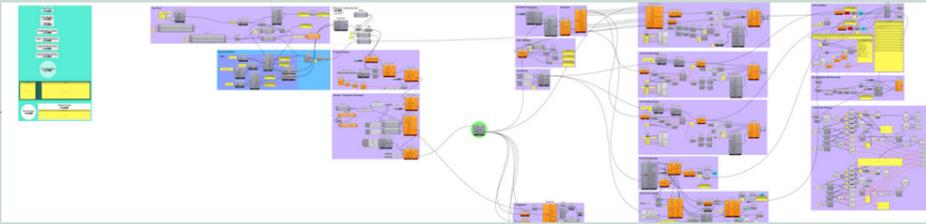
Output 3.2
Optimal R-Values



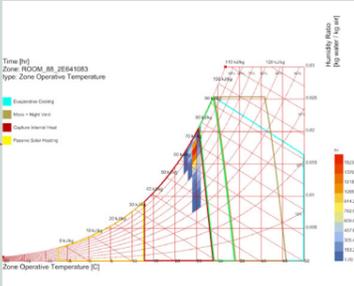
Input 4
Output 2.1 with 3.1 characteristics



Process 4
Passive strategy integration choice



Output 4
Energy consumption and comfort data



4.4. Data as a Design Guide

In a traditional project workflow, design information develops throughout the design process. Information can be divided into two information types: **prescriptive information** and **descriptive information**.

Descriptive information is industry standard and building codes. Prescriptive information is what is prescribed by the project team such as specific window types or use of certain materials (RIBA, 2020).

Descriptive Information

The proposed multi-objective workflow aims at developing knowledge at early design stages. Descriptive information is mostly set by local codes and standards relating to structural systems, mechanical and electrical systems, façade, roofing, floors and wall systems. with which architects can work to develop their ideas and build a firm design concept. It is present from early design stages as normative criteria has to be met. As the project progresses, the need for descriptive information is less required.

Prescriptive Information

Prescriptive information is defined at later design stages with little to no information at early design stages. The proposed workflow, through the stepped approach, opens the conversation between stakeholders towards defining project prescriptive information.

A study utilizing the proposed workflow can determine a specific window to wall ratio is required in order to reduce energy consumption. The window to wall ratio can be kept as prescriptive information to be utilized in later design stages. This can also be applied to material's thermal conductivity and thermal resistance. The information gathered from an early exploration phase can define such parameters to be included throughout the design process.

Such a methodology leads to an increase of prescriptive information that can be used from the early design stages and throughout the design process.

Defining building prescriptive information before a conceptual design phase allows the information to influence concept design and guide the technical design phase towards a building with a more conscious energy consumption.

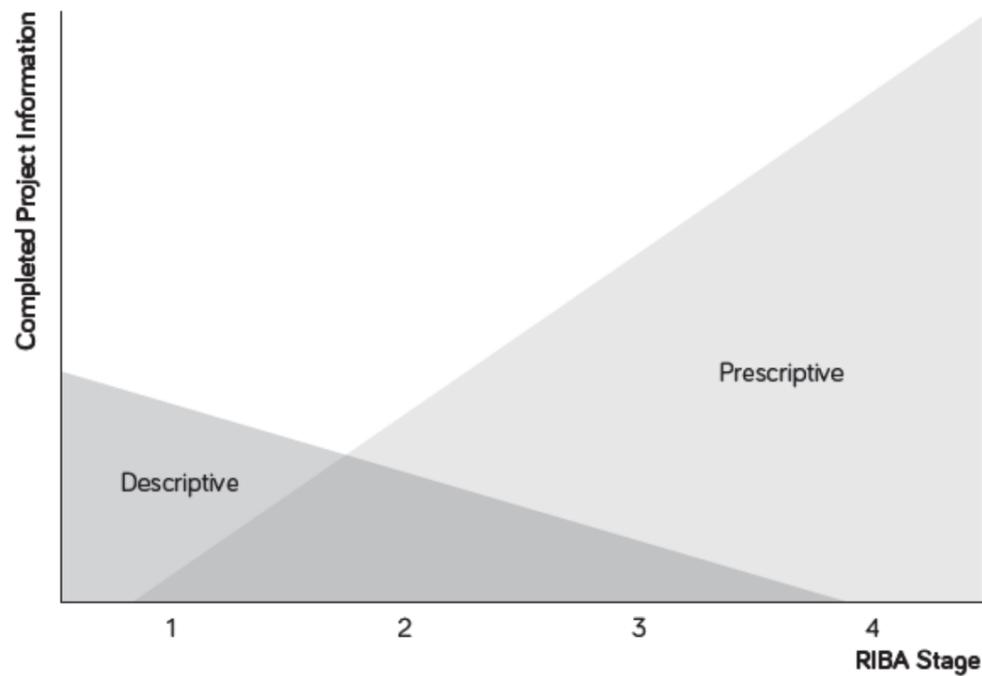


Fig 87: RIBA's 2020 Plan of Work Descriptive and Prescriptive Information Graph (RIBA, 2020)

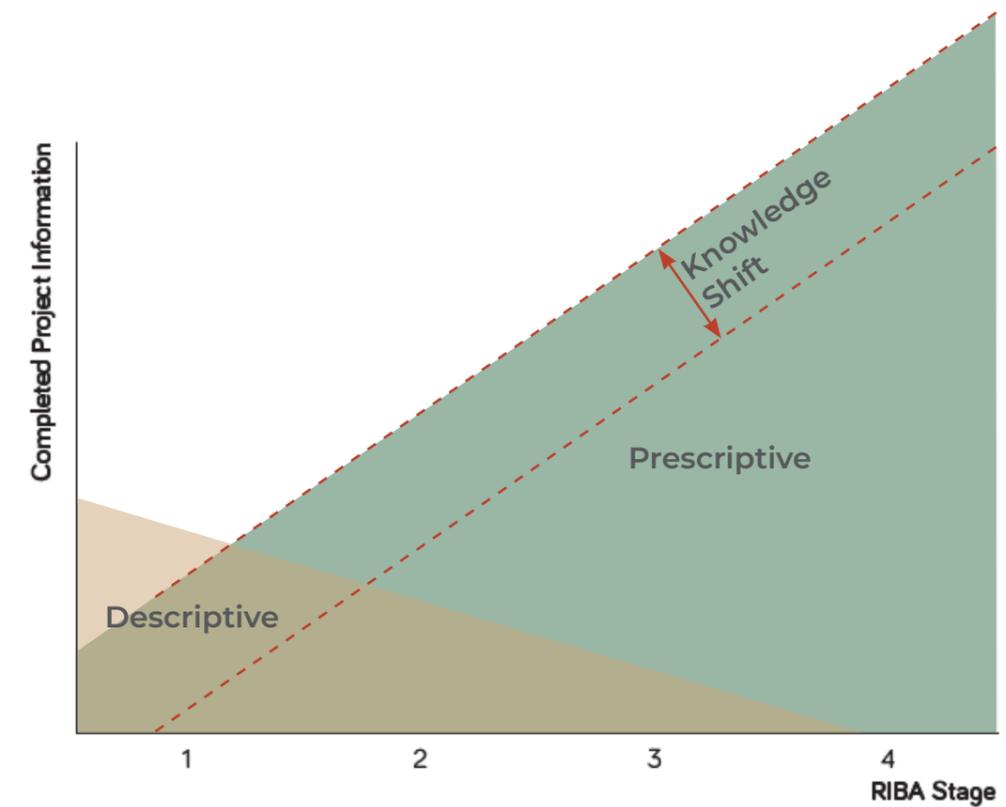


Fig 88: Modified RIBA's 2020 Plan of Work Descriptive and Prescriptive Information Graph by workflow integration

4.5. Impact of Optimization on the Design Process

Design processes are constantly changing, throughout briefing, design, manufacturing and construction of new buildings (RIBA, 2020). The integration of computational workflow in the design process has allowed for a more extensive exploration to be done at earlier project stages. The use of parametric modeling has changed the way in which we design and thus how our buildings operate in different climates (Manni et al., 2020).

Integrating an optimization workflow into the design process is the embodiment of parametric design; in this case, with an objective to reduce energy consumption and improve interior comfort. The proposed workflow does not shift design process responsibilities to an earlier stage, nor does it substitute stage aims or outcomes. The intent is to gather data and build knowledge so new information can be used to define later design stages.

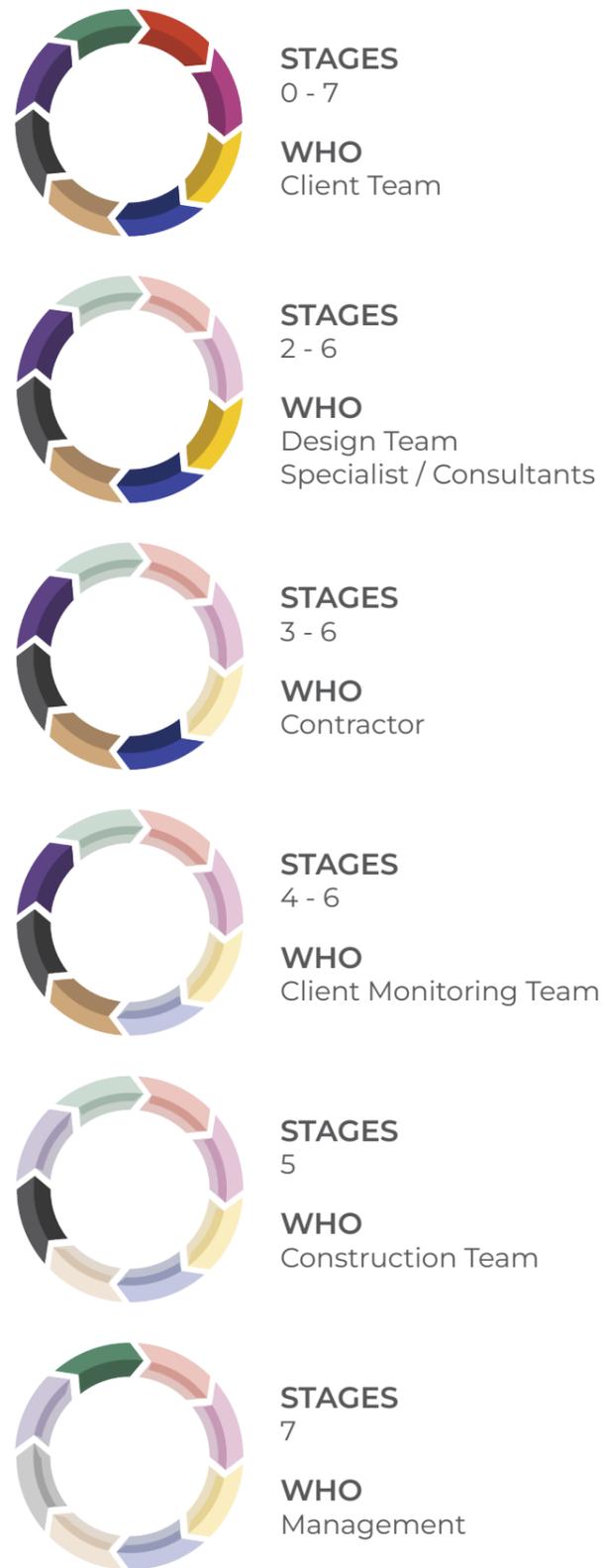


Fig 89: RIBA's 2020 Plan of Work - Team Role Inclusion per stages

Workflow Integration Exploration Post Stage 0 - Pre Stage 1

The optimization workflow establishes a relationship between local climate conditions, system parameters and building operation characteristics, aligning with Stage 1: Preparation and Briefing. Integrating the developed workflow between Stage 0 and Stage 1 aligns with project stage goals relating to project preparation and planning, specifically sustainability outcomes, aspirations and as a preamble to site surveys related to climatic conditions.

However, a design team is not usually part of these stages which makes design exploration limited. Furthermore, conceptual design is developed until Stage 2 once a Stage 1 project brief is completed with project program, feasibility studies and spatial requirements.

Workflow Integration Exploration Post Stage 1 - Pre Stage 2

When following the optimization workflow after a successful Stage 1: Preparation and Briefing, geometric explorations can take effect. Results can serve as comparison towards project sustainability objectives and design preferences regarding energy consumption and interior comfort levels. Simple geometric explorations shape the architectural concept and plan for strategic engineering requirements which will follow during Stage 2: Concept Design.

Inserting the proposed workflow between Stage 1 and Stage 2 can limit geometric exploration of architectural concepts as the workflow simplifies geometries from 2D extrusions.

There is a development phase where workflow users adjust and build experience into how much information is needed to guide the design; balancing an intuitive design based concept and a data-driven design.

The workflow's purpose is to build knowledge that will assist in the decision making process. It is not intended to define geometry but to inform the positive and negative aspects of certain design choices.

Instead of looking at the process as purely data driven or intuitive, an architectural workflow benefits from a data-informed approach; not dictating but guiding a decision making process.

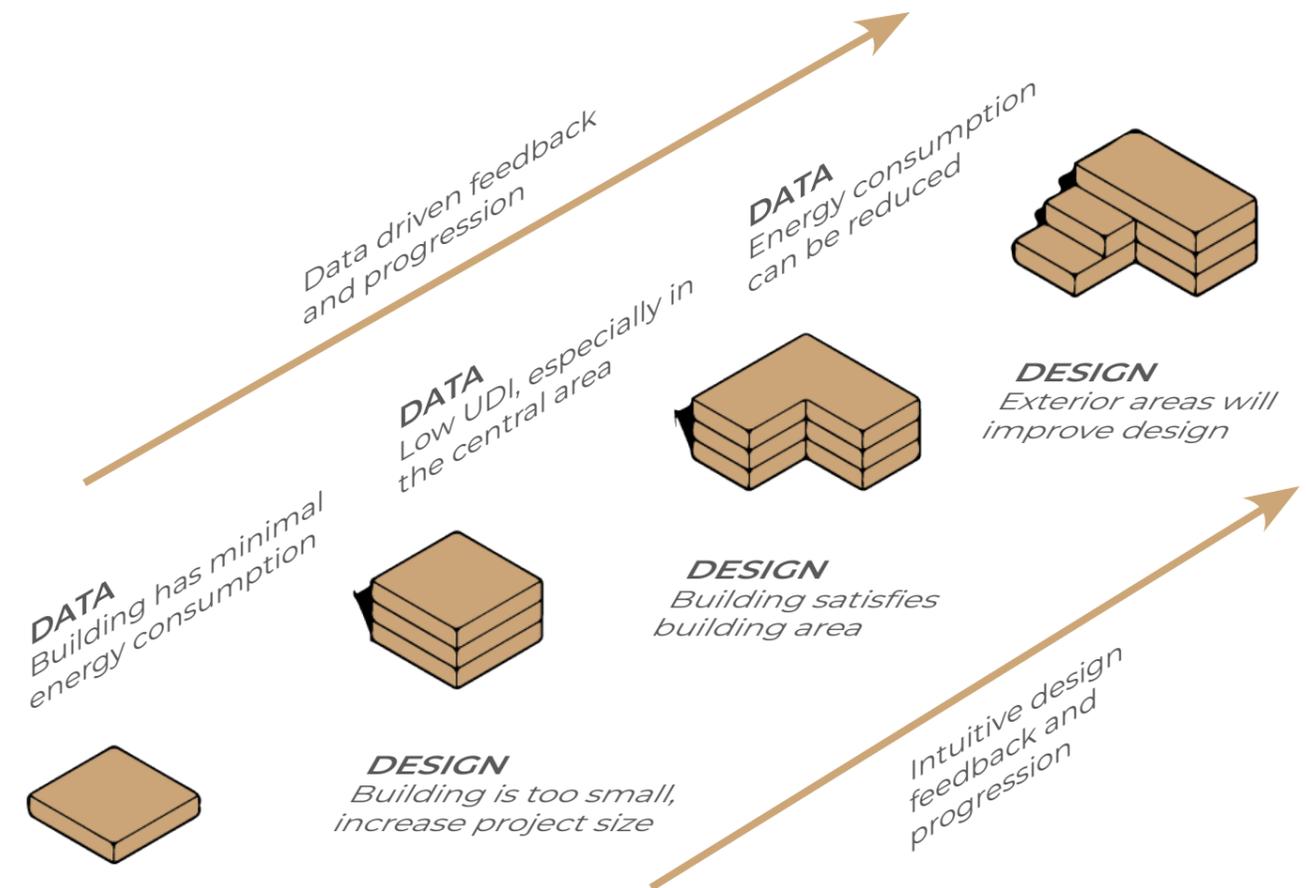


Fig 90: Example of dialogue between data-driven and intuitive design to formulate conceptual design

Workflow Integration Exploration Post Stage 2 - Pre Stage 3

Another potential workflow integration is after Stage 2: Concept Design and prior to Stage 3: Spatial Coordination where a simplified geometry from the conceptual design phase can be used to draw analysis results from the various multi-objective simulations.

During the Spatial Coordination phase, design studies and engineering analysis are usually carried out. However, if any significant change is to be made at this stage in the design process, a design concept re-formulation would be necessary.

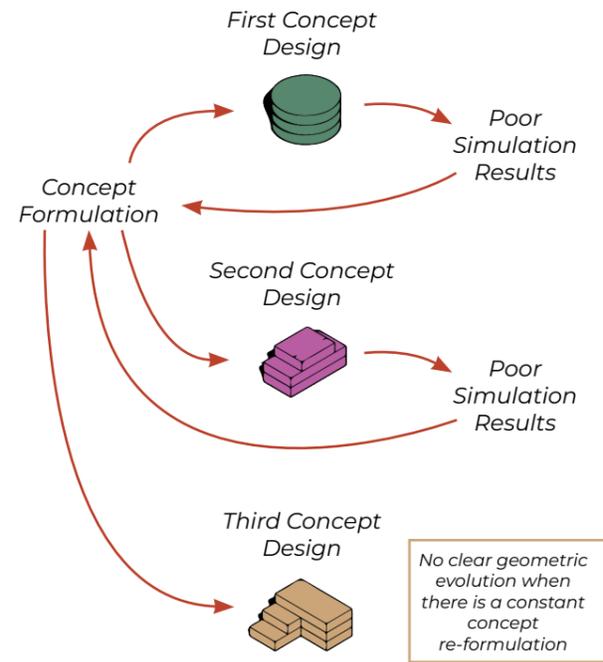


Fig 91: Iterative design process between concepts and results

Early Design Stage Workflow Integration

Developing a workflow for early design stages focuses on improving design efficiency through an informed approach, eliminating design concept re-formulation. The workflow guides the generation of an energy efficient conceptual design and develops prescriptive information to serve throughout the design process.

From all potential integration schemes, the most suited for an optimization workflow is after Stage 1: Preparation and Briefing and prior to Stage 2: Concept Design. Although a data-informed approach requires a balance between data and intuition, developed through experience, an optimization workflow has the most potential when informing an architectural concept.

In accordance with Evans (2007) early interventions in design have the greatest potential and the lowest cost. Implementing the proposed multi-objective comparison and multi-objective optimization workflow prior to the design concept develops knowledge and builds upon the architect's and engineer's experience related to energy efficient design.

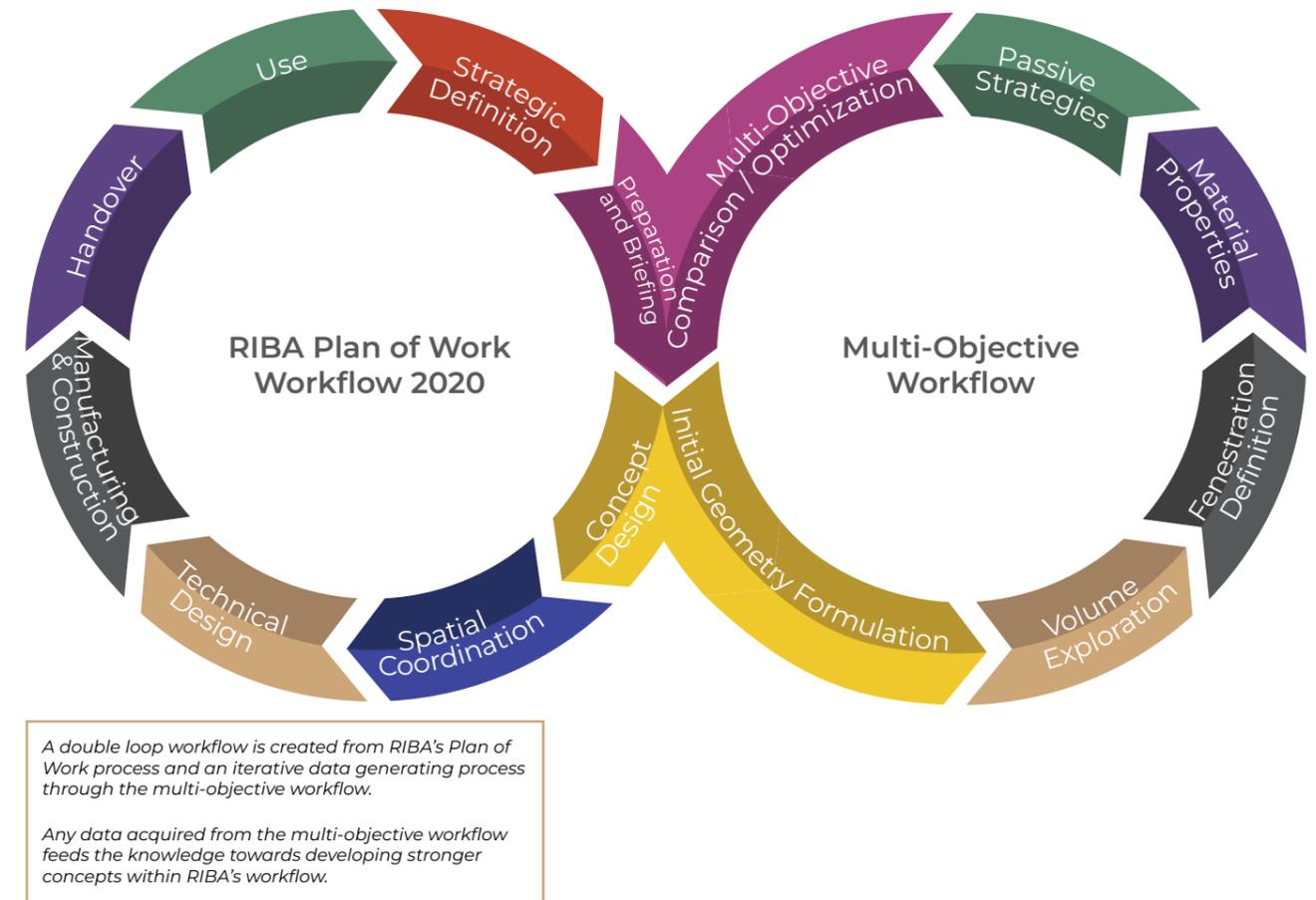


Fig 92: Summary of workflow integration into the design process established by RIBA's 2020 Plan of Work

5.1. Research Questions

5.2. Workflow's Key Aspects

5.3. Workflow Limitations

5.4. Development and Improvement

5.1. Research Questions

How can a multi-objective optimization workflow assist in early design stages towards a climate responsive design?

A multi-objective workflow has the benefit of looking at various design objectives to find solutions which satisfy designated criteria, instead of looking at improving only one building aspect. When combining a multi-objective workflow and an optimization process the solutions become a balance between design solutions and their fitness values. Knowledge on how design solutions operate with specific parameters presents trade-offs which can be evaluated to determine the best design option based on design priorities.

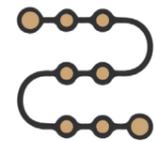
Concept designs focus on design exploration where knowledge is developed through design reviews to satisfy criteria and client needs. At this stage, prescriptive information rarely or scarcely exist which has an impact on building performance at later design stages. The purpose of integrating a multi-objective optimization workflow in early design stages is knowledge development. Information gathering and result comparisons assist in defining location and climate oriented solutions, comparing operational energy consumption and interior comfort for specific climate types.

Climate



- Considers **future climate** conditions
- **Impact** on design
- **Passive strategy** selection

Workflow



- **Parametric** modeling and exploration
- **Trade-offs** between priorities
- Build **knowledge** through stepped approach

Design Process Integration



- Data **informed** approach
- **Feedback** loop and design progression

The research focuses on climate responsive designs, steering conceptual design towards proposals with reduced energy consumption and interior comfort without the need to constantly require active systems. Energy saving measures focus on avoiding unnecessary energy use. Heating and cooling loads should be reduced on an annual basis by considering local weather cycles and their impact on the built envelope.

A climate responsive design will not entirely eliminate energy consumption. Through a workflow contemplating multiple design objectives such as energy consumption and interior comfort, consumption could be minimized without impacting a design's livability standards. Active systems would still be required to satisfy operational needs but their sizing can be minimized, saving operational costs.

An optimization process offers the most optimal solution to a design objective. Although knowing the 'best' solution becomes a key source of information, there is a limiting factor whenever project specific priorities are not addressed. An exploration through a multi-objective comparison workflow considers project by project design priorities (eg. Specific views or material preferences) and focuses on adapting other, less significant, design requirements towards a climate responsive design.

A multi-objective optimization workflow assistance in early design stages can offer the most optimal solutions to satisfy specific design criteria towards a climate responsive design. However, its usability is limited to the geometric options which, in most instances, show a constrained geometric variance. This does not mean the options shown satisfy design preferences. Including a multi-objective comparison workflow in parallel to a multi-objective optimization favors a hands-on approach towards design exploration; with greater freedom to satisfy design needs whilst developing knowledge on the energy impact and interior comfort levels at every design step.

Balancing qualitative and quantitative data towards a design solution satisfies client and sustainability needs. A hands-on-approach builds upon the designers' knowledge, creating a relationship between parameters and design performance. Design freedom and autonomy strengthen a conceptual exploration process with energy and comfort simulations informing design decisions towards a climate responsive design. Both a multi-objective optimization and multi-objective comparison processes are needed to have a data-informed design rather than a fully data-driven or intuitive design.

Climate Design

• What are the climate-responsive design strategies used per climate type?

Climate has a direct impact on building characteristics, especially when focusing on buildings without active systems for heating or cooling. For fully passive designs, building volumes in warm climates tend to cover a larger floor area, dissipating warm air throughout a larger volume.

On the contrary, constructions in cold climates tend to have a lower surface area to volume ratio. In warm climates, smaller window area reduces solar gains but also reduces ventilation, leading to larger infiltration requirements at a detail level.

Light constructions are also preferred for warm climates, avoiding thermal storage, the above being the opposite for colder climates. However, material choices influence building performance based on total thermal resistance and a window to wall ratio.

These conclusions have been supported by simulations for various climate types and their optimization process. The integration of passive design strategies can also be done for several climate types. Integrating a passive strategy is climate dependent, meaning there is no design that will fit all climates. Passive strategy characteristics are described in Chapter 2 and are developed based on previous research supporting their integration within a specific climate.



Fig 93: Passive design strategies used per climate type according to literature research, only one per climate type is shown.

• Which design principles support each other and what are the possible conflicts?

Certain design principles have a synergetic relationship, boosting their individual and overall performance when coupled with other strategies. Designing with multiple objectives requires a balance between achieving one objective over the other, avoiding commitment to one fitness objective, compromising a buildings' operations in other design aspects.

| Design Principles | Relationship | Explanation | Design Consideration |
|--|--------------|---|---|
| UDI and Solar Shading | Support | UDI levels can be improved in warm climates by integrating solar shading, this creates larger ventilation surfaces whilst reducing solar gains and maintaining UDI levels at an adequate standard. | |
| Mass buildings and Solar Gains | Support | Increased solar gains in mass buildings can be buffered for later use after solar gains are not longer active. This reduces temperature swings between day and night. | |
| Solar gains vs. UDI | Conflict | Large window surface area means more solar gains and, depending on the orientation, too much natural lighting, reducing UDI levels. Small window sizes improved energy consumption by reducing solar gains but impacted UDI levels through small amounts of natural lighting. | The objective is to find the smallest window size to still have an adequate UDI level for a comfortable interior. This way, cooling energy is reduced without compromising interior comfort levels. |
| Surface Area to Volume Ratio vs. Solar Gains | Conflict | Large surface area to volume ratio in warm climates are prone to larger solar gains, the opposite being the case for small surface area to volume ratio in cold climates. Cold climates would benefit from the gain and retention of solar gains through larger windows, avoiding heat losses through conduction. | Using skylights or materials with higher thermal resistance can reduce heat gains and losses through conduction and radiation. Shading devices during peak sun hours can further reduce internal solar gains in hot climates. |

Table 12

Design principle support and conflict table with design strategies to consider when facing conflicts between design principles.

• How can the effects of climate change impact the design decisions based on current climatic conditions?

The constant change in weather patterns due to the impacts of climate change modifies how buildings operate throughout their lifetime. Buildings are designed with a life expectancy between 60 to 80 years, over which local climate will become hotter. Designs focused entirely on solar gains are prone to a decline in their operative comfort levels due to excess solar gains.

Climate morphing considers future climate conditions, using the information to simulate and evaluate building operations under warmer climate scenarios. However, climate morphing does not take into account the impacts of climate change nor extreme weather events.

Climate change's impact on future climate conditions will exacerbate the results obtained from data morphing. Awareness into our planetary weather conditions and the transformative nature of weather patterns within local climates can develop a knowledge based approach. Similar to the proposed workflow, data morphing serves as a tool to develop knowledge. Although morphed data is used throughout building simulations, considering natural occurring weather patterns, it is crucial to understand the impacts of climate change or extreme conditions are not considered. This knowledge can have an impact on the final design.

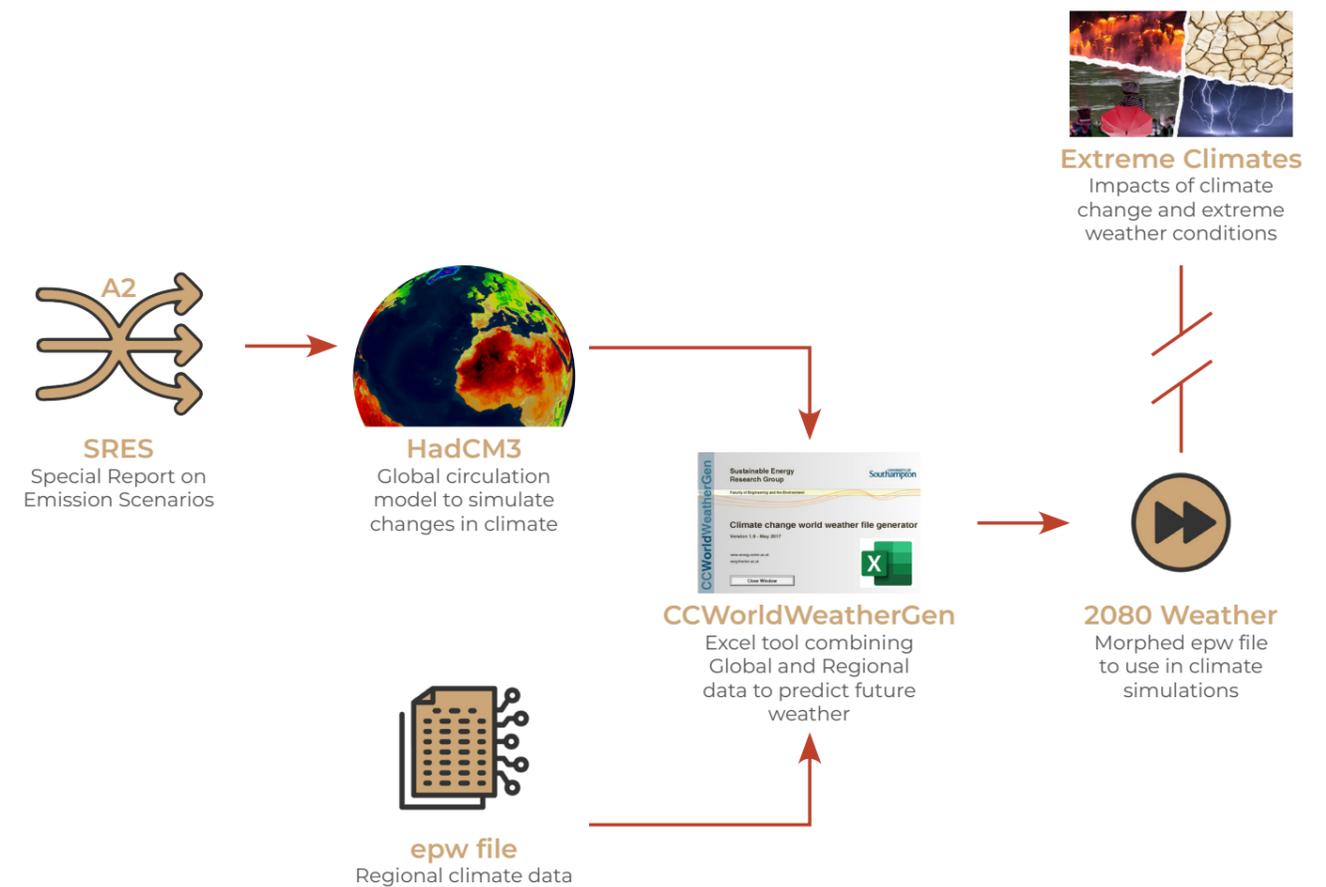


Fig 94: Climate morphing process showing the lack of inclusion of extreme climate conditions and global warming impacts on the morphed EPW file.

• How does a multi-objective optimization workflow empower design development?

Optimizing for multiple objectives generates several potential solutions to solve design requirements. Showing various designs satisfying a fitness objective offers a variety of solutions with the 'best' performance according to a fitness objective. Through a combination of a standard, intuitive design and a data-driven design leads to a dialogue between a building's operative numbers and the designer's or clients design preferences.

The balance between qualitative and quantitative data promotes rethinking and re-evaluating design solutions to tackle a design brief and its requirements.

• How can simulation data be integrated into current & future workflows?

The whole workflow functions as a knowledge gathering process where genome modification builds a relationship towards design performance. Simulation data generated and stored over a number of iterations functions as a study guide towards the designer, considering the working aspects for defined climate conditions. Optimization results, especially when used prior to a comparative design exploration function as initial

idea generators, reference designs and conceptual starting points.

Architectural projects never start from zero. Designer preferences, client reference examples or past projects have an influence towards subsequent designs. Simulation data can serve as a comparative approach and even as a potential benchmark to improve upon. Fitness values and design phenotypes have the possibility to improve design, knowledge empowers and it is up to the client and designer to decide how the information gathered should be used.

• What are the limitations from integrating an optimization workflow into a design process?

If the workflow solely contains optimization results as a tool towards design, there is a limited amount of knowledge generated. The design either becomes fully data-driven or intuitive and there is a lack of knowledge developed through the relationship between genome modification and fitness values obtained.

Limitations within the proposed workflow are mainly due to the oversimplification of geometries which can limit the analysis of desired conceptual designs or limit the creative process by viewing all potential designs as a series of boxes. Further limitations are described in section 5.3. Workflow Limitations.



Fig 95: Insertion of the proposed multi-objective optimization workflow within RIBA's design process and its relationship to the existing project steps.

5.2. Workflow's Key Aspects

Knowledge Development

Design workflows are evolving systems under constant adaptation as architects and engineers evolve their design methods and experiment with design tools and techniques. The proposed workflow is an expansion into a data gathering process where expertise grows throughout the design process based on information obtained at early design stages.

Future Climate Conditions

Energy consumption has a severe impact on CO2 levels which in turn accelerate the effects of climate change. There is a need to reduce energy consumption through smarter, energy efficient strategies. Climate-responsive designs integrate into the local climate, making weather patterns part of the building's functionality. When climate and building function in unison, energy gains and losses are used to the building's advantage as a way of managing thermal comfort.

With a constantly evolving climate, exacerbated by the effects of global warming, there is a need to consider future climate conditions when designing buildings lasting over 60 years. Integrating climate morphing into the design workflow uses climate predictions for 2080, approximating climate conditions to the ones contemporary projects will respond to. Designing for future scenarios defines passive strategies that will have an impact throughout a building's life cycle whilst considering the effects of climate change.

Benefit of Parametric Modeling

The workflow benefits from user input and data-oriented geometric manipulation allowing for the duality of a multi-objective comparison and a multi-objective optimization process. Parametric design establishes a relationship between stimulus and design, prompting a response.

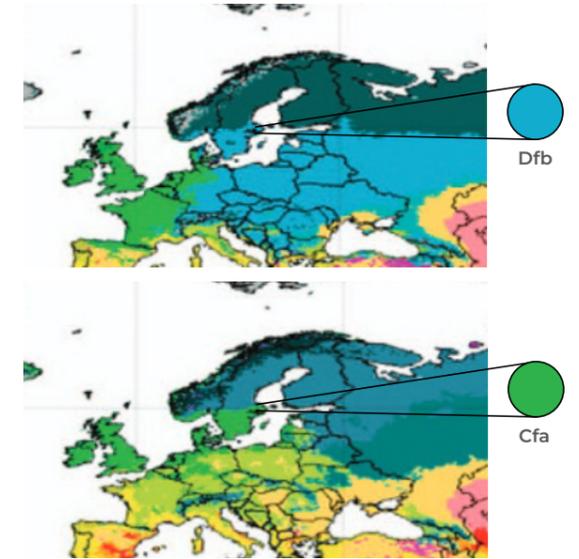


Fig 96: Current and future Koppen-Geiger climate map comparison

The ability to use parametric modeling and climate simulations through Grasshopper and Ladybug and Honeybee plugins respectively, gives way to both intuitive and data-centered geometric explorations without the need to constantly redesign geometries for simulation.

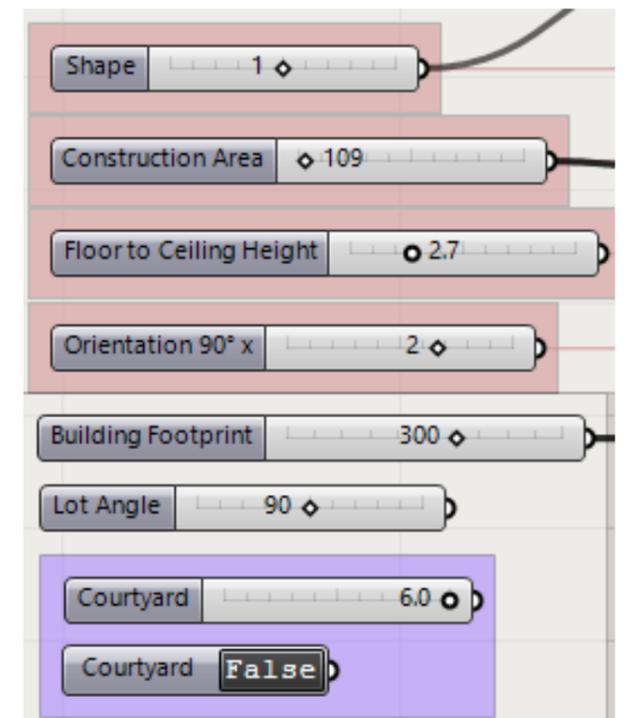


Fig 97: Genome value selection from the proposed workflow's Grasshopper file

Design Priorities & Trade-Offs

Implementing a multi-objective workflow in early design stages has shown to be an effective methodology towards gathering data prior to a concept design, serving as a guide towards the decision making process. Having the ability to compare qualitative and quantitative information promotes a dialogue between stakeholders and the design team, where design priorities are discussed and obtainable targets are set.

A multi-objective approach takes into account various factors which can be impacted by selecting specific simulation genomes. Looking at multiple fitness objectives, as opposed to one, offering a wider range of knowledge by looking at how certain fitness objectives are being met under certain conditions.

The proposed multi-objective workflow shows the resulting values for all fitness objectives being evaluated and allows for a selection to occur based on design priorities. Resulting geometries will inevitably vary if natural lighting has a higher design priority than cooling or heating loads.

Stakeholders and clients are given the possibility to select their preferences, fully aware of the trade-offs made along the process. Design flexibility, especially at early design stages, is necessary to avoid stifling creativity by purely focusing on objective achievements. The proposed workflow accomplishes the balance between a data driven and an intuitive design, resulting in a data-informed design.

Stepped Approach to Design

Having a stepped approach towards design builds upon the idea of data generation and increasing the knowledge obtained throughout the process. A stepped approach gives way to a selection of genomes and allows correlating data to fitness objective values building knowledge between cause and effect. The recurrent simulation process ultimately aims to develop designer's experience that can be applied in future projects.

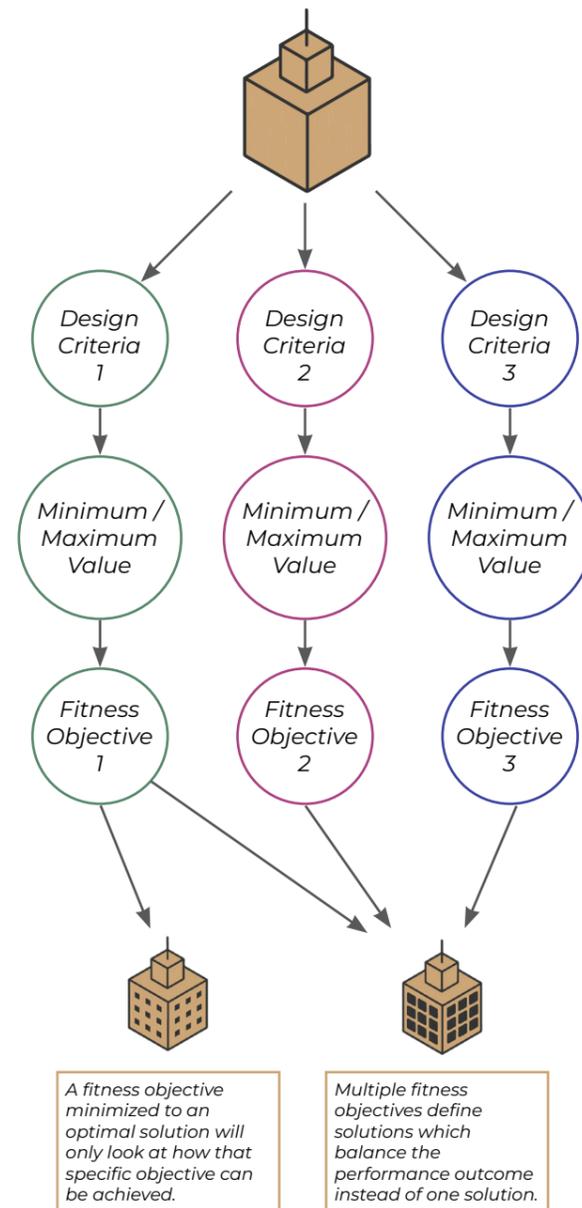


Fig 98: Illustrative approach to single-objective and multi-objective design

A stepped approach ultimately has limitations which affect the process and the results obtained. Viewing each building characteristic as part of a whole system prevents simulations and optimization procedures to analyze the building holistically. Each step is limited to the designated fitness objectives given whilst the rest are ignored. In the proposed workflow, thermal comfort is not considered until the material integration step; a characteristic which might be improved from earlier in the exploration process at a volume or fenestration level.

All fitness objectives could be included at each workflow step however, too many fitness objectives would complicate the decision making process and prolong an already longer design exploration process.

Tool as Project Engineer During Early Stages of Design

Acting as the project's climate engineer, the workflow offers design suggestions towards a more sustainable development. It can be considered as a tool for sustainable design but it also functions as a teaching application where several iterations can be checked for performance and where knowledge extracted throughout the process is applied.

Data-Informed Approach

The very first step of every new design is compiling what was learned from previous projects as a means to include strategies that performed accordingly and to note what could have been improved. Reflecting upon past experience and knowledge is part of the design process with a constant aim to improve and develop as professionals.

Being able to access data generated throughout the project is essential to retrace steps carried out during the design process. Step retracing serves as a means of understanding what could have been improved and what choices could have been different to accomplish better results.

Resulting Data

Results obtained from optimization simulations are varied throughout the stages, with each step showing a reduction in value range. The spread of fitness values per stage reinforces the benefit of using the proposed optimization workflow, showing there is indeed an improvement when integrated into a design process.

Results obtained throughout the comparative or optimization workflow are meant to be comparative values between a range and combination of possible genomes. Fitness values are not meant to be taken as final operating results as there is a manifold of factors which have not been considered during the simulation process. Nevertheless, the simplification of geometries shows consistent comparable results.

5.3. Workflow Limitations

Fitness Objective Limitations

Although the obtained results show feasibility, the workflow only focuses on a small portion of indicators which make a building comfortable. Focusing on only energy consumption and interior comfort metrics such as UDI and comfort levels through PMV and adaptive comfort, the workflow is limited in scope.

Certain factors such as glare can be deduced through UDI indicators but other aspects such as acoustic performance or interior air quality can't be determined through the proposed workflow. Nevertheless, at early design stages most of these indicators are not defined which reinforces the argument for their omission.

Process Limitations

During the third step for the proposed workflow material properties are selected. A simplification for the process was required due to the extensive nature of material combinations and properties. Only thermal conductivity was included in the workflow, considering the building element's total thermal resistance.

Material properties which impact thermal properties such as density and specific heat capacity had to be omitted since such properties are material dependent and will require material definition to calculate the values for an entire building system.

Integrating density and specific heat capacity values would have required a clearer material definition which does not occur prior to a conceptual design.

Passive Strategy Parametric Design Limitation

Initially, this research aimed at integrating passive strategies such as windcatchers, roof ponds, trombe walls, solar chimney, solar shading and sunspaces into the design workflow. Although research indicated their integration is possible per climate type, including these passive strategies into a simulation workflow proved harder than initially considered.

Passive strategies had to be simplified, ultimately using the passive strategies integrated in Grasshopper's Ladybug. There was an attempt to link roof pond construction properties to the parametric model, including material density and specific heat capacity. Nevertheless, Honeybee's Model to OSM component does not support multi-layered building systems.

Further research is needed to translate passive strategies into parametric models in order to quantify their performance, this falling beyond the current research's objectives.

Context

Every simulation carried out throughout the process ignores the influence of context. Projects are usually surrounded by factors which influence performance, whether these are built or natural. The proposed workflow does not take into account building surroundings due to their uniqueness on a project by project basis.

It is possible to include context in a variety of ways in order to obtain site specific results:

1. Obtaining 3D data from databases such as 3Dbag in the Netherlands
2. Model the context prior to any geometric exploration
3. Simplify context with a set of parametric walls with parametric distance settings.

5.4. Development and Improvement

Workflow Development

There is definitely a need and a benefit in utilizing multi-objective optimization workflows in early design stages. Using data generated throughout the simulation process guides the architectural concept development, aiming to satisfy design criteria discussed throughout the optimization workflow. Furthermore, genome values used to obtain the preferred phenotype and performance metrics can guide prescriptive information throughout the remainder of the design process.

A multi-objective optimization workflow is not able to provide a definitive value to be used in a design decision but it is able to provide a range of possible solutions and approximations which lead to a better performing project. The workflow is considered a guide, an educational framework towards energy conscious design.

Future Work

Without a doubt, the workflow will need to continue updating to accommodate newly acquired knowledge and entwine with actualized plans of work. Architecture is a constantly changing field and with the use of computers changes occur at a faster pace than before.

Future work is needed to better define geometric possibilities. The current 2D simplification serves simple concept designs but the results will greatly vary as geometries become extensively more complicated. With current artificial intelligent tools it would be an interesting step to integrate image to 3D design workflows towards a geometric exploration, opening the possibilities to more varied and detailed geometric possibilities.

The current workflow separates multi-objective comparison and multi-objective optimization due to time constraints

and lack of interoperability between the proposed tools. Developing a unifying tool to include both possibilities but also to include machine learning from previous simulations could greatly increase simulation speed. Rethinking the workflow might be necessary in order to ensure there is a balance between qualitative and quantitative data.

Finally, greater emphasis could be provided towards qualitative data in the form of potential floor plans based on a 2D geometry. Image searching for similar floor plans to the one being simulated could bring more ideas to the table, increasing stakeholder and design team knowledge.

Improvement pathways can stem in multiple directions, especially in a constantly evolving computational space. Nevertheless, the research present here has shown to be an important first step towards discussing the importance of a multi-objective workflow.

Approaching the decisions through qualitative and quantitative data with the aim of reducing energy consumption and improving interior comfort levels has proven successful at early design stages.

It would be an unparalleled opportunity to test the workflow in a real-life setting to determine other optimization strategies or potential workflow integration methods. Testing how well the workflow assists in reducing CO2 emissions, curbing the effect of climate change and improving our built environment.

Chapter 6

REFLECTION

6.1. Introduction

6.2. Relation with Master's program

6.3. Research influences

6.4. Work assessment

6.5. Academic, societal and ethical aspects

6.6. Project transferability

6.7. Comparison with existing processes

6.8. Novel aspects of research

6.9. Reflection on personal growth

6.1. Introduction

The objective for this thesis project was to develop a workflow to assist the design process with the aim of reducing energy consumption and improving interior comfort. Focus was directed towards passive design criteria which impacts a building's operations such as volume, orientation, window to wall ratio and materials. Furthermore, the integration of passive design strategies such as thermal mass, roof ponds, night ventilation, etc. can be included in the design, having a direct impact on a building's energy load.

6.2. Relation with Master's Program

The Master of Science in Architecture, Urbanism and Building Sciences focuses on innovation through a multidisciplinary approach to create solutions for the built environment. My thesis bridges the gap between architects and engineers through a collaborative tool to inform decisions at an early design stage.

The Building Technology track focuses on a building's technical aspects, the direction taken for this research focused on the climate's impact towards the built environment combined with a computational workflow to determine a design assisting methodology.

To develop a workflow, knowledge of architecture design processes and technical analysis is required to provide key data leading to informed decisions. Merging design and technical fundamentals allows for data driven explorations resulting in less energy consumption and improved comfort levels within the built environment, leading to a more sustainable future.

6.3. Research Influences

As a methodology, literature reviews guided and influenced research for multi-objective optimization and early design stage workflows. For the former, the importance of problem re-formulation became a key component within the workflow development as informed decisions led to an improved outcome. Workflows on the other hand solely focused on a single step approach, mainly building volumes.

However, research within a multi-objective optimization workflow for windows and material selection was widely available which allowed me to use these processes as inspiration towards a stepped approach within early design stages. A stepped approach, rather than a single optimization workflow, allowed to break-down the problems at each stage, inspired by the importance of a problem re-formulation which allowed to view and compare results at various design stages.

For a workflow development it is important to consider the end user. Differentiating between multi-objective result comparison and multi-objective optimization was required as the time to complete these operations is widely different. Furthermore, a user-friendly interface will simplify the complexity of multi-objective workflows, acting as a front to a complex geometry manipulative back-end development.

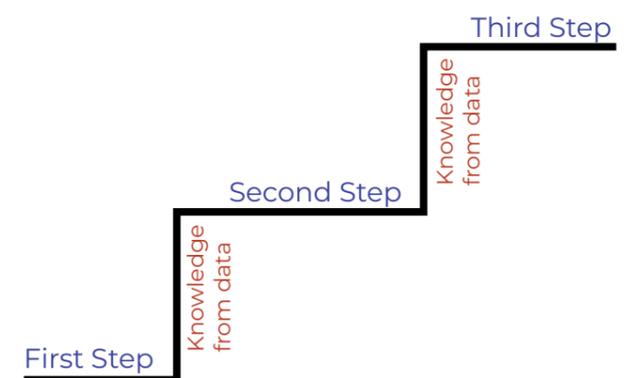


Fig. 1.1. Workflow's stepped approach diagram

6.4. Work Assessment

The methodology explores both qualitative and quantitative evaluation strategies which offer a wide range of informed choices tailored to the user. On a short-term, multi-objective comparison, the evaluation focuses on quantitative data, offering options to explore other design preferences in a specific situation.

Multi-objective optimization provides side to side comparison of various models which could assist in the decision-making process. However, multi-objective optimization is not integrated as a short-term method and, although qualitative data is provided, it becomes more complex to integrate it into a short-term multi-objective comparison workflow.

Exploring other multi-objective optimization tools might give a more integrated design approach. Nevertheless, this does not address the computational time required to complete an optimization workflow for a short-term analysis. To enhance a dialogue between short-term and long-term data the workflow could be structured in such a way that mass information can be stored in a database and retrieved from the workflow's pre-run simulations database.

6.5. Academic, Societal and Ethical Aspects

Academically the project links architectural design with building technology. Bridging two study tracks whilst contemplating faculty goals towards a sustainable future. Using the developed tool offers informed decisions about site and comfort, using the knowledge acquired from the initial exploration towards concept and design development stages. By linking intuitive design with data-driven approach, the workflow raises awareness towards our design choices. Knowledge acquired through several design iterations will develop experience and build correlations between design choices and their effect.

On a societal level, it provides information about trade-offs between two design choices, allowing users to create informed decisions with a tailored outcome specific

to a user's design priorities. Although the analysis is carried out in early design stages, the information obtained can guide future decisions, contemplating there is an overall aim to reduce energy consumption and improve interior comfort. The developed tool, with a simple user-interface, makes design analysis more accessible and does not become overwhelming when seeing a back-end grasshopper file. This empowers society into exploring their own design choices and engages them within the design process.

The developed tool is a preamble to design and the data generated is to create comparison scenarios and should not be taken as the design's total energy consumption. There are many other factors which influence energy, and this should be properly addressed within the tool or throughout the design process to avoid creating unrealistic expectations throughout a building's operation stages.

There is also a degree of inaccuracy with using EPW files for climate analysis as these are generated using older climate data. This is partially mitigated through a data morphing process to reflect climates in 2080 but these are still climate predictions without considering the impact of global warming.

Overall, there is a positive impact in academics and society, making building analysis available to a wider population. Ethically it must be clarified that the information is to serve as a guide and not as a final result.

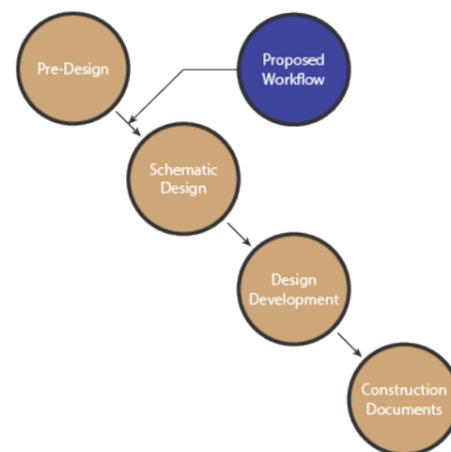


Fig. 1.2. Workflow's integration into a traditional design process

| Strengths | |
|-----------|--|
| 1 | Simple interface to manipulate geometries and define design preferences |
| 2 | Integration into an existing design workflow without disruptions but as an additional tool |
| 3 | Makes building climate analysis accessible to a wider population base who previously relied on intuition or costly consultants |

| Opportunities | |
|---------------|---|
| 1 | Awareness of energy consumption is growing due to high energy prices. Similar workflows can build upon this research to improve design strategies |
| 2 | Early stage optimization can be incorporated into a design software. Parameter manipulation is minimal at early design stages |
| 3 | Designing with the intent to reduce energy consumption will lead to a less intensive energy consuming future |

| Weaknesses | |
|------------|--|
| 1 | Has only been tested on flat roof geometries |
| 2 | Does not account for context which might have severe impact on lighting conditions |
| 3 | Detailed material properties such as density and specific heat capacity can't be added in detail |

| Threats | |
|---------|---|
| 1 | Weather stations and EPW data is outdated to current weather conditions |
| 2 | Integration into a workflow requires balancing quantitative data with qualitative preferences |
| 3 | Requires time and effort to integrate into an already existing system |

Fig. 1.3. SWOT Analysis for the developed workflow and its integration into the traditional workflow

6.6. Project Transferability

A key aspect of this project's results is the transferability of the data obtained. Although the data is generated at early stages, the workflow maintains all the necessary details constant, allowing the comparison of results from various geometries and a manifold of design preferences such as windows and materials. The tool can be used on any number of geometric shapes (shape extrusions have been tested so far) and can be compared with any previous results.

Furthermore, the workflow could be developed in the future to include the possibility of assessing an already existing geometry (irregular volume) from a fenestrations and materials focus. Lessons learned from passive design strategies, although not fully integrated into the workflow, serve as useful knowledge for future researchers or project developers as information tables per climate type were compiled from various sources.

The research serves both as a database for passive design strategies per climate type and a workflow which can be further improved by future researchers aiming to curb energy consumption.

6.7. Comparison with Existing Processes

A multi-objective comparative and optimization model integrates into the design process. The model is not and will not be sufficiently developed to substitute a traditional design process. The benefit of developing a model for early design stages is the effortless integration into the traditional design process even prior to schematic design.

Multi-objective optimization workflows are usually integrated at later design stages (usually post-design development) where changes can be costly and comparatively less efficient than at early design stages. Decision making is enhanced by introducing data-driven options coupled with qualitative and a user's design preferences.

The workflow is versatile due to its decoupled properties from a front-end interface and a back-end design process and analysis. For designers with grasshopper experience, modifications can be made to suit specific projects such as adding context or refined material properties.

6.8. Novel Aspects of Research

The innovation is a front-end user-friendly interface allowing non-technical users to develop design options for their desired space. Using the Human UI plugin for grasshopper, users are able to avoid the complexities of a grasshopper interface and focus solely on the key components having an impact on their design.

Throughout the workflow development it was also discovered there is a need to separate workflows based on the user. A short-term multi-objective comparison can offer almost real time data to clients, owners, and nontechnical stakeholders. A multi-objective optimization is used for data generation and comparison at a larger scale which required more computing power and time and will not usually be addressed during a design meeting if the results have not concluded. However, a subsequent design meeting (after optimization simulations conclude) can provide useful information in the form of pareto fronts and parallel coordinate plot to find potential new solutions to a design problem.

6.9. Reflection on Personal Growth

This thesis project has become a challenge at various stages and required knowledge from a bachelor's degree in architecture and knowledge obtained throughout the Building Technology course at TU Delft. Furthermore, new knowledge was acquired throughout the process. From the use of new software to a methodological thinking approach which could have an impact on the workflow's outcome. The logic behind a grasshopper script is the interconnection of elements which start a chain reaction when operated. Careful planning was required in order to obtain the desired results. What began as a trial-and-error approach turned into a careful planning process through mind mapping and diagrams. Overall, this thesis project has impacted my planning methodology and honed my skills in grasshopper and the various plug-ins used throughout the development.

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