The New Normals: Architecture Under Climate Change Uncertainty

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Keywords: Passive Design, Climate Change, Uncertainty, Bioclimatic Design, Architectural Resilience

This paper discusses design research that utilized an existing project development phase to test a methodology for involving multiple projections of climate change in the design a of a present-day institutional building. In the paper an initial argument is laid out for the need for this type of design method. This is followed by a brief explanation of the methodology borrowed from charrette scenario planning and climate impact assessment. A schematic design that is the result of this planning process is then displayed as a jumping off point to discuss design decision making under the auspices of an unknown future climate system and the need for site-climate calibration in passive architecture. This design is the composite of three possible "optimal" buildings that represent one program designed for using climate scenarios from three major socioeconomic carbon emissions pathways. The final design is the resultant interpretation of these three futures and the needs they impose on the program and the building as a formal bioclimatic object. Concluding remarks follow the presentation of the design and decision making theory behind its elements.

ARCHITECTURE AND CLIMATE CHANGE

Buildings must now be designed to endure the impacts of climate change. In addition to the more common services they provide these systems and buildings must also shelter vulnerable populations from extreme temperatures, allow children to safely learn during lengthy monsoon seasons, contain and isolate populations through pandemics, protect families from intense and fast moving wildfires, all while not increasing the severity and likelihood of these events through the emissions of more greenhouse gasses that are currently trapping heat in the atmosphere. This task has already begun to change architecture as a formal language, putting a more significant onus on passive solar design than on HVAC systems, although these are still paramount. This transformation is due to the fact that the derivation of form has, for decades, been subscript to abundant and economically inexpensive sources of energy that could be used inefficiently to either heat or cool spaces.[1] However, their true cost, externalized spatially and temporally has come due and will be increasingly expensive going forward—with an outsize portion of the cost being forced onto communities that are not responsible for running up the tab, leading to a need for design less reliant on fossil fuels and more on the buildings relationship with solar radiation and the consistent temperature of the ground.

The cost of inefficiency is coming due in the form of more dangerous and erratic extreme weather systems, increased potential for widespread pandemics, collapsing ecological systems, water and food shortages is the result of the emissions of greenhouse gasses (GHGs) from anthropogenic sources at a pace that cannot be matched by the natural carbon cycle.[2] The atmospheric concentration of GHGs, deemed safe at 350 parts per million (ppm) rests at 411ppm at the time this document was penned.[3] That is 5ppm higher than two years prior when the Special Report on Global Warming of 1.5°C was published by the Intergovernmental Panel on Climate Change (IPCC) extolling the danger even the smallest amount of increased warming (current warming is between 0.8°C and 1.2°C) and the dire need for rapid decarbonization of human systems.[4] There is a clear imperative that fossil fuels need to be removed from the designer's pencil box, immediately. They can no longer be relied upon to provide stable comfort conditions, protect buildings from intruding moisture, or keep buildings from falling down.

This paper focuses primarily on the former of these three aspects buildings by attenuating architectural form and exposure, building components, and detailing to multiple climate change scenarios. Early stage design decisions around building form, solar exposure, solar control, and orientation to the wind have significant impacts on end stage energy-demand.[5] [6] A great deal of scholarship has been spent on studying building optimization from before the Moderns, through Mies and the Olgyays, and in contemporary architecture with the introduction of advanced computational tools and design approaches based on site-climate analysis.[7] However, site-climate analysis from the perspective of climate change is understudied due to the exclusion of extreme weather events and the uncertainty found between projections of climate models.[8]

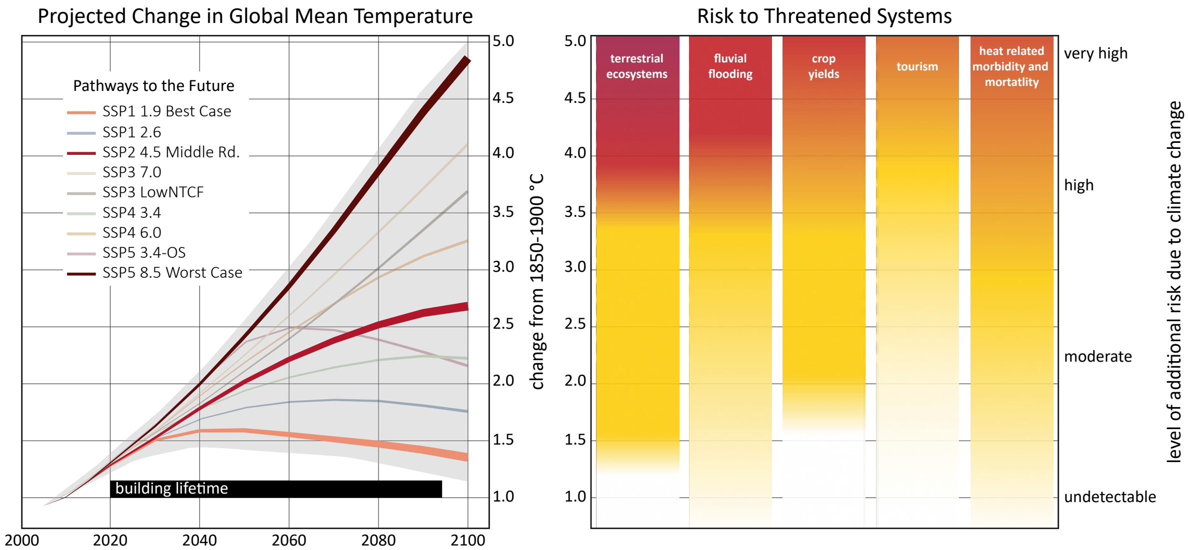


Figure 1. This figure is adapted from the IPCC's Fifth Assessment Report (IPCC, 2014). It describes the increasing amount of disturbance to certain systems with increased levels of warming, translating the range of uncertainty into a clearer range of impacts.

Uncertainty Is the Only Certainty

Passive design hinges on the understanding of a building's relationship to the bounds of the site's regional climate system, inter annual variability, and extreme events such as a longer than normal duration of dangerous heat or unhealthy air quality from near or far wildfires. However, as the climate continues to change, the regional climate system, traditionally considered a static element in building design will become less similar to the design boundaries of that passive building.[9] Designing for climate change uncertainty would be a simple exercise if climate scientists were able to model with 100% accuracy and certainty the way the ocean and atmosphere has reacted and will react to fluctuations in atmospheric GHG concentration , and anthropocentric emissions were with certainty locked in.[10] This is however never going to be the case. Climate models are developed to encompass the uncertainty surrounding natural and human systems in order to provide a range of potential warming for climate impact assessments to follow through on. This range or potential climate futures and the severity and likelihood of impacts between those futures, shown in Figure 1, prompts the question of how a building can be designed to operate passively within present conditions while also intending to meet one of many possible futures.

ARCHITECTURE OF UNCERTAINTY

In this design study a single building was designed for using three climate change scenarios, derived from a set of global climate scenarios known as the Shared Socioeconomic Pathways, commonly referred to as SSPs.[11 12] These three designs, viewed as architectural climate change models, were then used to inform a design for the program suited for present day climate conditions, but prepared for the changing climate conditions as well as client needs expected under the different climate scenarios, determined through a scenario planning charrette. The difficulty with this is that a passively designed building presents different formal and material relationships with each potential future climate to remain optimized in its production of comfort and services for occupants.

Each climate change scenario is envisioned as an entirely different site from which to begin the design process. Each requires different passive design strategies, such as optimal solar orientation for heat gain or in one scenario heat loss or different vegetative strategies for shading design based on projected growing season and water availability. The resulting designs are summarized in Section 3 along with a fourth design meant to be the starting schematic design for the project. This final design was developed by interpreting the most necessary aspects of the three scenario-based designs for the present day that also provides for a resilient and adaptable future for the building. Figure 2 presents a generalized workflow for this project, the specifics of which are covered in following sections.

Context

The "client" for this project is exploring a new opportunity for an institutional building to support academics, public outreach, and agricultural research on an organic farm in Central Pennsylvania. The program for the building is roughly 7,800 square feet, broken up between laboratory and classroom space, a commercial kitchen for event support and culinary classes, a 100-person event hall, several small faculty and support offices, a root cellar, and general mechanical and service space. The design process presented in this study followed a robust visioning of the needs for the farm and client and was framed as a climate impact assessment for future architectural design work and project development. This involvement enabled the project to be placed in the context of decision

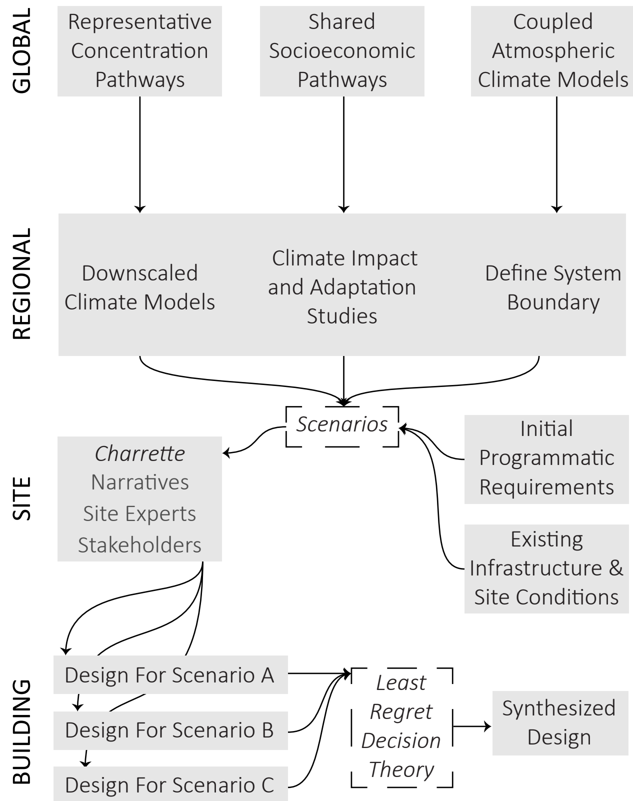


Figure 2. The framework for the project operated across four scales with each step in the design process focusing in closer to the building.

makers that can weigh the different concerns of the project against the potential impacts suggested by the climate models.

Site-Climate and Climate Change Impacts

Climate change projections are the result of significant endeavors in computational modeling and climate science. The inputs to the models typically detail a trajectory for anthropogenic GHG emissions over the next two centuries. The most commonly referenced model outputs typically come from pathways of GHG emissions that are derived from assumptions about social and economic activity, the SSPs mentioned earlier.[13] These pathways provide modelers with a set of possible emissions scenarios that provide the range of possible warming levels seen in Figure 1. The outputs of these models are framed as changes in variables such as near-surface air temperature are relevant most often on a continental to regional scale. The models use monthly time scales and cells on the order of 100-300 square kilometers to represent the Earth's atmosphere, ocean, and cryosphere numerically. While important for larger climate impact assessment these outputs can only provide the design process with trajectories of change and not actual design conditions. Downscaled regional climate models and impact assessments, while more resolute and contextual to a specific site still only offer a notion of what types of impacts may be expected, not yet translating the climate model output into information relevant for the design of a single building.

Within the building energy model domain there is a wealth of research being conducted on how to best downscale and calibrate these models to better aide the design process.[14] In an age of computational modeling these efforts typically translate into augmented EnergyPlus Weather (.epw) files or numerical boundary conditions that represent a potential future state of a site's climate. While important for energy modelling and parametric-based design, this study chose to ignore them in order to demonstrate a method of designing for climate that did not rely heavily on computational methods, as a great portion of practice has not yet adopted computational modeling.[15]

Designing With Climate Uncertainty

To replace the optimizing process found in computation modeling an established set of design recommendations was utilized as *optimal design* for a given type of climate. These recommendations were formulated through climate-based design research in the 1950s and 60s by Victor Olgyay and Aladar Olgyay and published in *Design with Climate: Bioclimatic Approach to Architectural Regionalism* (1963).[16] The *Bioclimatic Approach* classifies the climate of the US in to four zones: Cold, Temperate, Hot-Arid, and Hot-Humid. Through site-climate analysis and physical building modeling the approach resulted in urban and building scale design recommendations that are meant to temper the impact of the climate, producing highly efficient dwellings.

The site for the project in question is currently situated in the Temperate climate zone but is expected, like most regions, to warm with climate change. The degree to which the region is expected to warm changes with different socio-economic climate scenarios. In this study three scenarios are covered: SSP19 (Best Case Scenario), SSP45 (Middle of the Road), and SSP85 (Worst Case Scenario).[17] The three selected here represent the full range of warming possible under all established set of scenarios available at the time this project was being conducted.

The scenarios and model output data were downscaled to the site in two ways. First, through a method known as climate analog mapping, made into a web-accessible tool by Fitzpatrik and Dunn (2019).[18] This method compares the distance between an initial multivariate distribution and other potential comparable distributions to ultimately find a match, referred to here as an analog.[19] The process compares the projected climate of a location (the project site) to other historical climates of many other locations, identifying candidates that have, in the present-day, a climate that is not too dissimilar from the projected climate of the site. Fitzpatrik and Dunn performed this analysis for two climate scenarios, Middle of the Road and Worst-Case scenario, while the Best Case scenario is considered to have an analog of the present day climate, temperate.[20] The result of this process is an identification of the climate system at the end of the century for the site under three different scenarios, translating the climate model data into three potential site-climate conditions from which to design. The end of century climate period (2070-2099) was chosen as it represents the midpoint of the of potential building's expected lifespan if built now.

This study also incorporated framework for planning decisions known as backcasting.[21] Backcasting is not about defining the future through generative material, but on deliberating on what processes and action might lead to one or more generalized future outcomes. In doing so a more generative and participatory planning process can be undertaken. Its use here allows the designer to posit different architectural responses to each potential end-of-century climate before returning to the present-day question of design. This in turn enables a decision-making process aimed at designing fixed elements so they are most appropriately suited to meet the needs of the future.

The uncertainty present in this framework introduces the need for one final element in the methodology, a decision-making paradigm. Many such paradigms exist and have been used in climate adaptation and mitigation studies that account for deep uncertainty, from cost-benefit analysis to more complex multicriteria decision theory.[22] The decision framework used here is a non-probabilistic theory known as *least regret,* which is aimed at reducing the amount of regret any future generations might have when looking back on the decisions made in the past under uncertainty.[23] Least regret, or the minimax regret criterion, is applicable to buildings due to its ability to best insulate a decision from low-probability, high-impact events which are of particular concern to building performance.[24]

Stakeholder Engagement

The physical changes due to climate change were not the only factors explored in this design study. The three scenarios were explored in a charrette setting to determine if different programmatic responses would be required of the building under different climate scenarios. This process follows on work done to make the global climate scenarios applicable to sub-national and regional decision making.[25] [26] The scenario planning workshops were held early on in the design process with two groups of nine stakeholders for the project, ranging from those knowledgeable about the academic needs of the project to those that would be responsible for developing financial support, as well as the client's project manager. In this process stakeholders were placed into groups organized by three scales: Regional, Institutional, and Site-specific. For each global climate scenario, a set of impacts were constructed based on the scenario and regional climate impact assessments that correspond to those scenarios. Each narrative was read to the groups and they were asked to respond with how they thought the impacts of climate change would influence the institution at their scale. The responses were in turn used to construct "extended" climate scenarios that were more appropriate for the project than global scenarios. These narratives were in turn combined with the analogs to create more holistic worlds within which to design.

The outcome of the climate analog study and scenario planning workshops can be seen in Figure 3, where the analog maps are presented, along with general passive design strategies for that climate and a collage developed to represent the final narrative.[27]

FIXED OBJECT FOR A FLUID TIMELINE

The task of designing for the present day given a range of possible climatic and programmatic futures begins with the end of the century designs framed as bioclimatic ideals. These ***Ideals*** revolve around a common schema for general massing and program distribution, but beyond that were designed with the notion that differences would arise in orientation, foundation, structure, interior arrangements, envelope, openings, shading, natural ventilation, and material concepts. A glimpse of the three ***Ideals*** and the resolution building as they map out to these elements can be seen in Figure 4. The following sections provide a brief explanation of the decision-making process involved in the design of each element in the present-day building following the lessons learned from the scenario-based design process.

Orientation

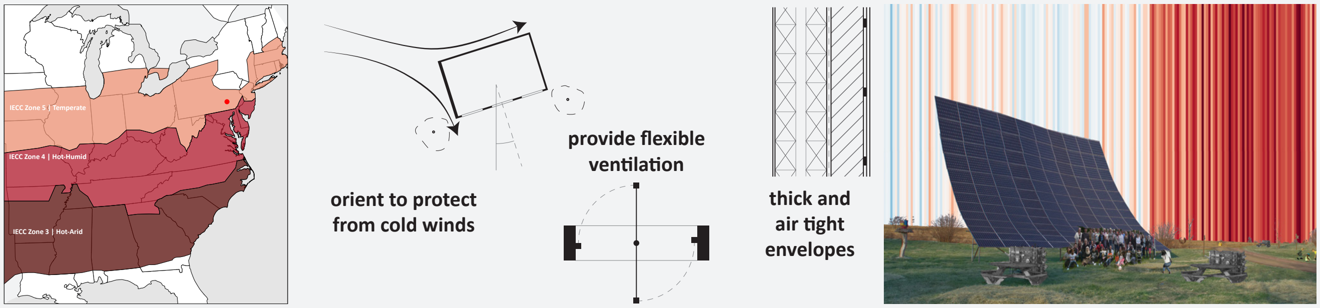
The building has two orientations, one that suits the site and one the projected economic situation. The foot of the building is rotated 5° east of south to align with the topography of the site, a gradual rise from south to north that runs almost exactly along the east to west datum of the site. The roof of the northern mass is set on a different plane. It was expected, from the Worst Case scenario, that photovoltaic power generation would one day be desired, if not immediately. Thus, the roof plane is set to the optimal orientation for the power generation from the sun - 30° east of south.

Foundation

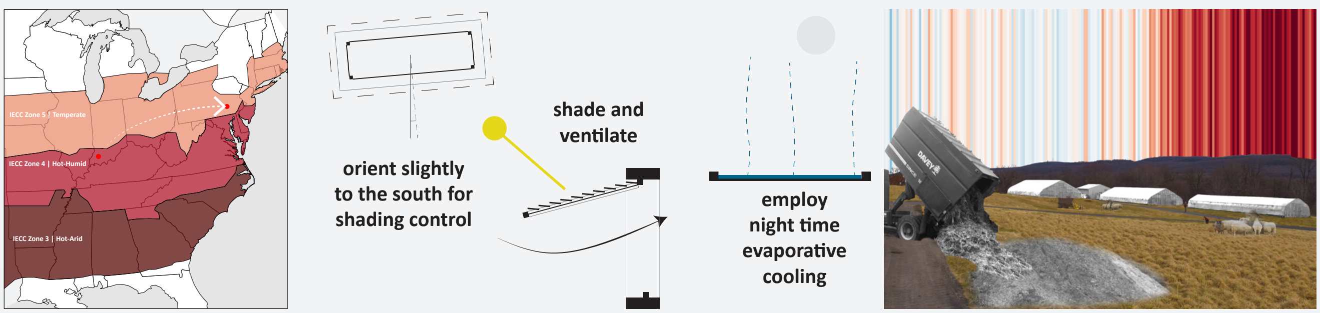
No single scenario dictated the design of this element as it was clear in each that a low carbon and low-impact foundation would be necessary. A helical screw pile with a gabion retaining wall holding back the excavation walls. This system allows the building to move away from cement entirely and be more carbon performative than a traditional stem wall or slab foundation. The advantage is that the piles, which can be reused can be sourced from retired fracking wells as well as reused when the building is decommissioned.

Structure

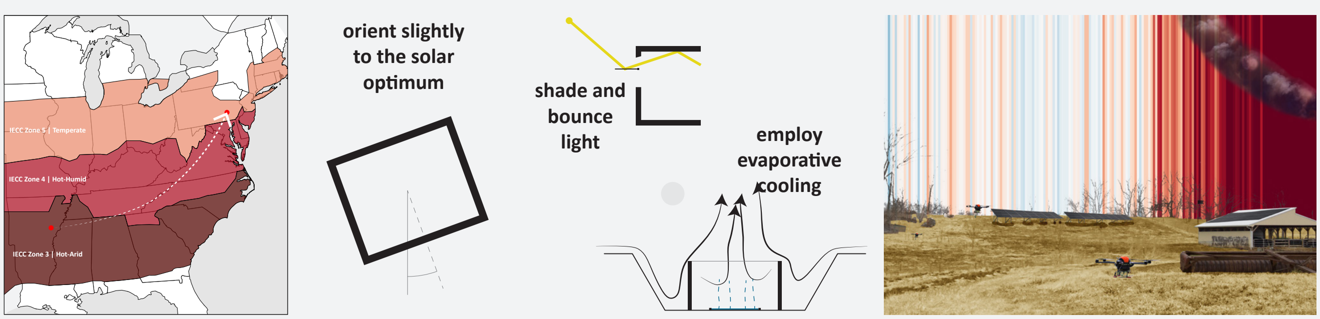
The structure of the building was determined from early on to be that of mass timber, post and beam construction to continue with the existing language of the farm structures. Sizing



Under the Best Case Scenario (SSP19), Pennsylvania's climate has not changed markedly from its historical temperate system. This is due to all of society gradually embracing sustainable practices and simultaneously managing mitigation and adaptation while reducing inequality and elevating poor communities. The region continues to experience all four seasons, with the expectation that extreme rainfall will be a factor to consider. The site is expected to be more heavily trafficked, requiring a larger public presence of the building as it will become a stronghold for advanced agricultural research and practice.



Under the analog for the Middle of the Road scenario Pennsylvania experiences a warmer and more moist climate. It is the product of a stagnant society, filled with inequality and barriers to both adaptation and mitigation. Population decreases along with global wealth into the latter half of the century. The climate is slightly warmer, with four seasons, although less intense. The humidity is also higher, leading this analog to be termed Hot-Humid, in line with bioclimatic climate zones. The farm's practices do not change markedly from the early 21st-Century with a moderate amount of public traffic and a reliance on biomass for compost and energy production.



Under the Worst Case scenario Pennsylvania experiences a hot-arid climate. It is the product of a technologically driven, adaptation-forward society that is fragmented regionally with a high global population spread evenly around the world. The region is warmer and drier than the early 21st-Century climate, now termed a Hot-Arid climate. The winter season here is much less significant with rare snowfall, leading to the shoulder seasons being similar and warm. Work in the fields is difficult due to intense heat and poor air quality. Thus the building will be utilized more and expected to remain cooler.

Figure 3. The three scenarios are presented here for their calculated analog locations, general passive design strategies, and collages that were produced as the outcome of the scenario planning process.

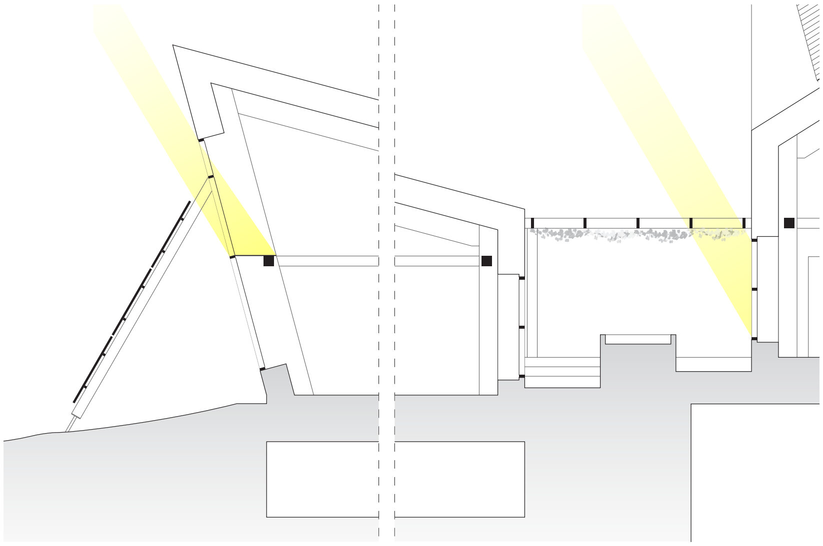


Figure 4a | Section Looking east with summer sun (60º) under Best Case conditions.

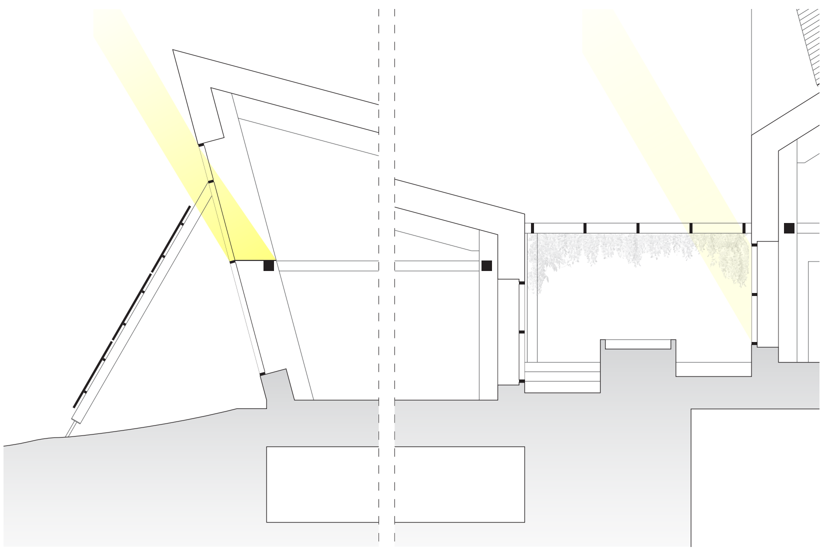


Figure 4b | Section Looking east with winter sun (60º) under Middle of the Road conditions

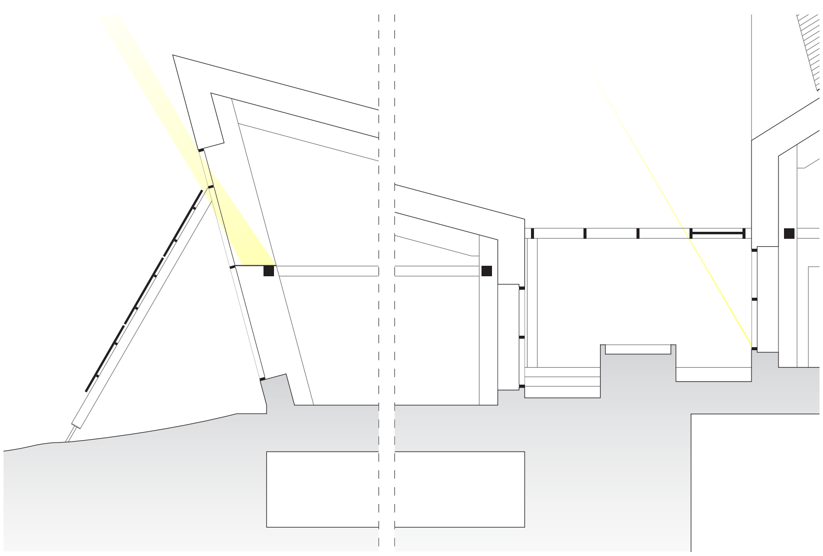


Figure 4c | Section Looking east with winter sun (60º) under Worst Case conditions

Figure 4. The shading system was designed to be adaptable to various climate scenarios using the same infrastructure in the adjustable PV panels and vegetated trellis that could accommodate a fixed panel if necessary.

differs in the first three for the roof beam, due to the difference in slope and thus length of beam - a large difference is not necessarily present. However, it was deemed important to follow the orientation of the roof to the solar optimum with the preparation of the roof structure for the load of photovoltaic panels. This load dominates the north structural design, while in the southern building it is the inclusion of an intensive green roof.

Envelope

In the three scenarios each envelope was designed following precedents discovered for each analog in the passive house database.[28] However, while more difference was expected this led to similarly thick envelops, as insulation thickness does begin to plateau in its effectiveness after a certain point.[29] The commonality between all three though was for an envelope that could be assembled and disassembled if needed changed, bespoke SIP panels. The resolution envelope is primarily dictated by the needs of temperate climate, as in the other two scenarios heat control is more focused on ventilation and shading. Therefore, a thick envelope of wood fiber board is used, but with exaggerated drainage planes and ventilation cavities to manage high volumes of rainwater expected across all scenarios and potential high humidity expected in the Middle of the Road scenario.

Openings

Openings vary across the three scenarios. In the Best Case, a southern exposure with more openings that will be shaded for warm weather allowing heat gathering during colder months, while in the Middle of the Road scenario only a clerestory is provided while north façade windows are privileged for indirect light gathering. The Worst-Case scenario sees a good deal of glazing on the southern façade, but these will be shaded with the installation of photovoltaic panels and are already shaded in part by the cant in the building wall. In resolution the scheme of the Worst-Case scenario is taken albeit with smaller windows. The caveat here is that the envelope need be designed to allow for new openings to be introduced if the building isn't performing well either thermally or from a daylight perspective.

Shading

Shading is gradually increased as the warm season stretches due to high average temperatures. From the Best Case scenario to the Middle of the Road the shading envelope almost entirely covers half the window, and eventually in the Worst Case scenario only a small period remains when direct sun can enter any openings. In resolution the southern building is shaded by the solar canopy and the cant in the wall, with appropriate solitary form for low winter sunlight. Interior light shelves are also used to push incoming sunlight deeper into the southern building. The façade of the north building and the courtyard are shaded with a vegetated trellis that under the first scenario could be used for growing such productive plants as hops. Or in the case of the Middle of the Road scenario a denser vine such as wisteria. Under the Worst Case, vegetation becomes an unlikely option as it would require water resources that may be in short supply. Under these circumstances a fixed shading panel could be fixed to the trellis.

Ventilation

The same general scheme for ventilation was used in all three scenarios, the direction of natural winds into the buildings using lower openings and the use of a natural stack effect for exhaust as the air warms. The major difference is in the degree to which the stack needs to be exaggerated, which is much more in the Middle of the Road and Worst-Case scenario. The major difference between these two is then in where the air is coming from. In the Worst-Case the air would likely be too hot to use directly for ventilation, thus a tempering effect is necessary, pulling air from the cavity space beneath the floorplate. This effect is transferred to the resolution design. The ventilation system could begin by using natural currents and outside air as a source but switch over to a tempered air source if necessary, using low to floor vents in a displacement ventilation scheme. The final design compromises between the two stack-effect design heights due to the slope of the roof, with the low point drawing from the Worst-Case scenario and the apex from the Middle of the Road.

Interior

The expectation was that through the scenario planning process, more diverse programs for the building would emerge. This was not however the case. While there was mention of potential momentary use cases – such as first aid facility in the event of a natural (or health) disaster, no new permanent programs emerged. The only shift was in the third scenario in which more interior space was required for laboratory work, as it would be expected less field work would be done due to the challenges of extreme heat. While not as significant a change as expected, the lesson is not lost. The interior space in the synthesis is slightly larger to accommodate future growth, and is also planned with light moveable wall systems that can be reconfigured without major modification to the building or building systems. This also present in the design for the floor assembly in which a raised floor with a large cavity would be useful for expanding or moving services.

Material

Material choices relate in the context of the models to the roof and how it engages with direct solar radiation. In the Best Case scenario, a green roof is employed to sink some of the radiation, while in the Middle-of-the-Road scenario a reflective white is used to reduce the possibility of the roof as a heat sink to near zero. Cladding the roof in photovoltaics is the option for the Worst-Case, which is not thermal choice but rather one that is the result of the economic circumstances of the scenario. In resolution, the more compact southern volume features a northward facing green roof, but the use of

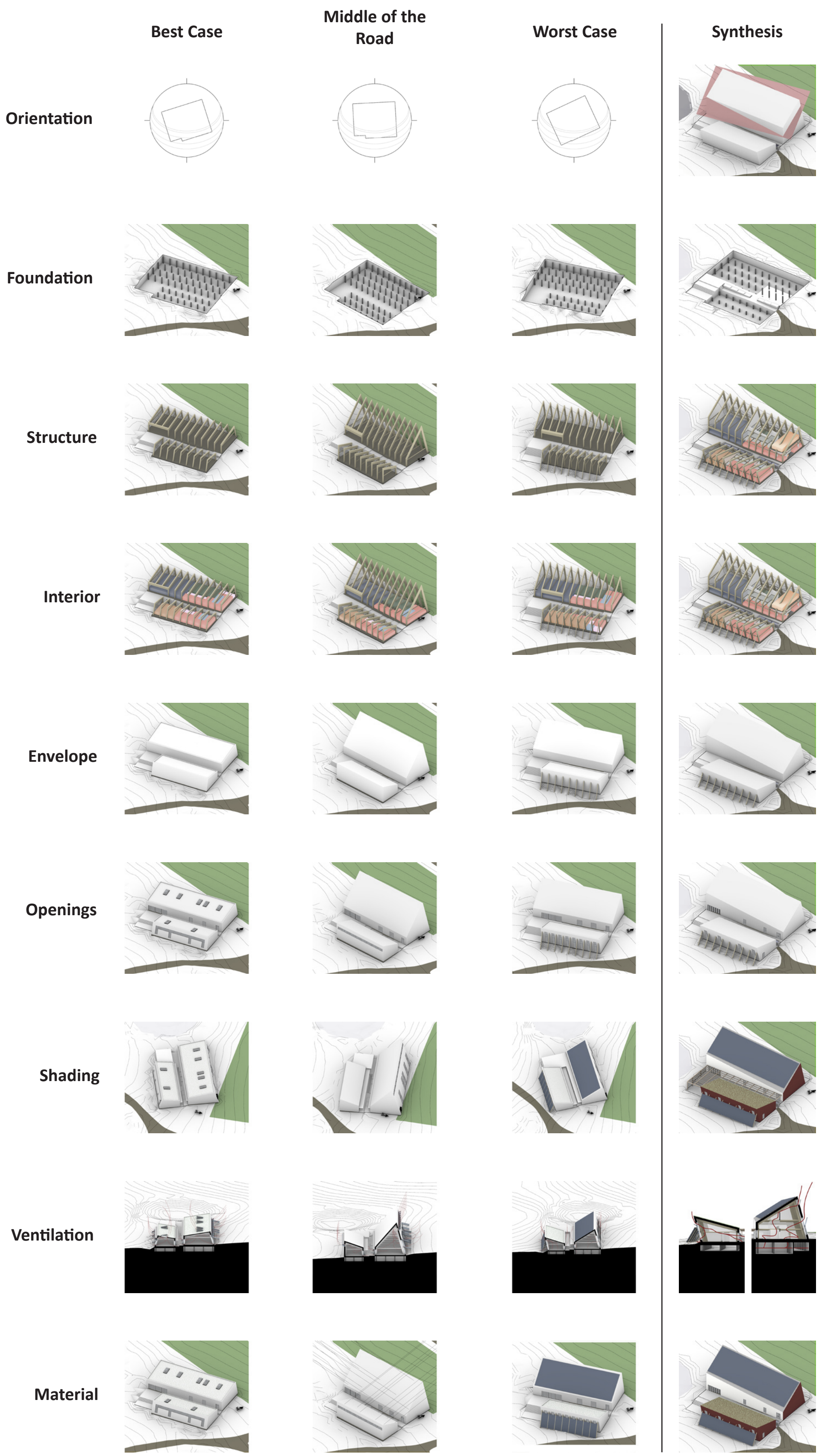


Figure 5. The resulting models of each scenario based on climate scenario and the resolution design.

reflective roof paneling underneath the expected photovoltaic array on the north building. The reasoning here is that it is not initially necessary to reflect all incoming sunlight and other treatments may take control. The façade would be clad in a dark red timber board to keep in line with the existing large structures of the farm and provide some surface area to act as a heat sink. The façade of the courtyard however is treated with a bright limestone façade. The effect here is twofold, to reflect sunlight captured in the courtyard into the buildings improving daylight access without compromising thermal integrity and to provide a thermal mass for the exterior space which could benefit year round from either heat regulation or excess heat.

Element Summary

The building elements in the context of time and uncertainty can be view as either fixed or adaptable. Fixed elements, such as orientation should be designed the knowledge that they are unlikely to be altered over the projects lifetime and should be decided upon appropriately. Easily adapted elements such as shading, showing in Figure 4, should be planned for the present with the notion that they will likely require retrofit one or multiple times in the projects lifetime. There were several elements that were expected to change dramatically under each scenario, most notably the program and interior arrangement. It is suspected that this would be the case if the building were in a more urban setting and served a wider range of potential occupants.

TOWARDS A FRAMEWORK FOR DESIGN UNDER UNCERTAINTY

Projections of climate change and the context that underlies them offer architects a rich landscape of data and socioeconomic projections to work from. The assumptions and narratives can be utilized to generate worlds in which buildings can be designed to meet the needs of specific futures. In this design exploration the uncertainty in climate change projections was employed as a driver for the design of the building. This methodology is meant as an initial framework from which architects can involve the uncertainty of climate change projections in their own work. This proposed framework is not meant to declare one decision making paradigm as more important than another, as these criterion are subject to the stakeholder's interests and appetite for risk. It does however, introduce the need to consider decision making under uncertainty as a part of the architectural design process, similar to advances in civil engineering as resilience becomes a primary metric.[30] Introducing this type of decision making early on in the project will allow designers to accept the limits of the design space and design for the decision making paradigm while also developing co-benefits within the project, as seen with the inclusion of structure and orientation for photovoltaic panels.

The type of decision-making theory employed is significant in the trajectory and resilience of a building, but hinges on the inclusion of site and project relevant projections of climate change. The AEC industry is not yet prepared for this. Global climate models and their outputs are complex and require expertise to navigate. Tools such as those developed by Fitzpatrik and Dunn for detecting analogs begin to make this process more conducive to practice but are still not tuned specifically to building or urban design. A similar sentiment can be applied to the use of decision-making theory applied to climate change. Further research and implementation are necessary in incorporating the work of both fields in architectural practice if building design is to meet the prescient need of complete and rapid decarbonization .

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27. This format does not permit the expansion on the downscaled narratives themselves, but they and the entire project can be viewed at https://justinfmccarty.github.io/bioclimaticensemble/ and https://justinfmccarty.github.io/bioclimaticensemble_pt2/

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