CLIMATE—CARBON—EQUITY

Making Sustainable Design Concepts Accessible for All

by

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Submitted to the Department of Architecture

in Partial Fulfillment of the Requirements for the Degree of

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CLIMATE-CARBON-EQUITY

MAKING SUSTAINABLE DESIGN CONCEPTS ACCESSIBLE FOR ALL

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ABSTRACT

Climate has a significant influence on how buildings perform, and how we design and build buildings impacts the climate. Therefore, the most effective sustainable strategies for low-carbon buildings are heavily influenced by the climatic context of the project. In this thesis, I present the development, validation, and application of an early-stage design analysis method called *climabox* as a toolset to evaluate the potential for low-carbon building strategies in any location for which climate data is available.

By presenting reliable bioclimatic information in a clear, intuitive format, the approach enables designers and consultants worldwide to make actionable, sustainable design decisions from the beginning of a project forward. The methodology has been implemented in a web app called *ClimaPlus* that is accessible on any web-enabled device.

The web app has been successfully tested in a Massive Open Online Course (MOOC), launched in collaboration with MIT Energy Initiative (MITEI), to teach sustainable building design as part of the *Future of Energy Systems* MicroMasters program. The goal is to make easily accessible and actionable design guidelines available for learners who want to develop energy-efficient and low-carbon building concepts anywhere. With a total enrollment of over 40,000 learners worldwide, I discuss the challenges and lessons learned from delivering the introductory, university-level sustainable building design course.

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GLOSSARY

American Society of Heating and Air-Conditioning Engineers (ASHRAE)

Chartered Institution of Building Services Engineers (CIBSE)

Bioclimatic - building strategies that respond to regional climate(U.S. Green Building Council 2014)

High ventilation - provides sufficient air change rates resulting in indoor air temperature following outdoor air temperature. Thermal mass buffering of indoor air temperature is restricted.

Low ventilation - provides low air change rates sufficient for fresh air, but indoor air temperature will remain higher than outdoor air temperature due to internal heat gains.

Climate or weather data - hourly, site-specific values of representative meteorological data, such as temperature, wind direction and speed, solar radiation, and relative humidity. For locations where climate data are not available, the designer shall select available weather or meteorological data that best represents the climate at the building site (ASHRAE 55-2013).

Adaptive model - a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters. It is the method for determining acceptable thermal conditions in occupant-controlled, naturally conditioned spaces (ASHRAE 55-2013).

Thermal comfort - the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ASHRAE 55-2013).

Acceptable thermal environment- a thermal environment that a substantial majority (more than 80%) of the occupants find thermally acceptable (ASHRAE 55-2013).

Operative temperature- the uniform temperature of an imaginary black enclosure and the air within it in which an occupant would exchange the same amount of heat by radiation and convection, as in the actual non-uniform environment. It is calculated in accordance with Normative Appendix A of ASHRAE 55-2013.

MITEI- MIT’s hub for energy research, education, and outreach, with a mission to develop low- and no-carbon solutions that will efficiently meet global energy needs while minimizing environmental impacts and mitigating climate change (https://energy.mit.edu/).

Massive Open Online Courses (MOOCs)- free online courses that are available for anyone to enroll, providing an affordable and flexible way to learn new skills, advance career and deliver quality educational experiences at scale (https://www.mooc.org/).

edX- an American massive open online course provider created by Harvard and MIT. It hosts online university-level courses in a wide range of disciplines to a worldwide student body (over 40 million users by 2021), including some courses at no charge (https://www.edx.org/).

Audit learners- online learners that register for a MOOC at no charge and do not receive a certificate.

Verified learners- online learners that enroll in a MOOC by paying a course fee and receive a certificate when completing the course with a passing grade.

Active learners- a term used by the author to describe learners who participate in at least 50% of the course contents, including lecture videos, compression questions, and assignments. Other MOOC course define active learners with different minimum participation requirements, which could be as low as watching one lecture video or one blog post.

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PART I: INTRODUCTION

Chapter 1 - Climate – Carbon – Equity

Figure 1-2.1-1 Building in hot, cold, or temperate climates now share similar technologies, an indicator that climate is being ignored in building design

Mainly because we care a lot about mindful living and protecting the climate, environmentally conscious building practices have become ever more important. All regions across continents are experiencing the adverse effect of climate change, and there is an urgent call for actionable solutions in all disciplines. According to the Paris Agreement, United Nations Framework Convention on Climate Change (UNFCCC 2015), the goal is to limit global warming to well below 2 degrees Celsius, at best to 1.5 ^{o}C, compared to pre-industrial levels. And, to achieve this long-term temperature goal in a carbon-neutral world by 2050, global greenhouse gas emissions shall be significantly reduced.

Currently, buildings are responsible for 38% of global emissions (UNEP and IEA 2019). Global buildings sector emissions increased by 2% in 2018 from 2017 levels, and final energy demand rose by 7% from 2010. Increases were driven by strong floor area and population expansions. With 68% of the world population expected to live in urban areas by 2050 (UN DESA 2018), requiring the built area to almost double, there is a need for a concerted effort for a dramatic and ambitious transformation to a net-zero building stock by mid-century (Burrows and Laski 2020).

There have been a lot of advances in technologies in the building industry – what was scarcely imaginable a few decades ago in terms of climate and comfort regulation has now become a reality in cities around the world. We can bring air conditioning to the desert and heat to the coldest part of the Arctic, and people can be comfortable. An unintended consequence of the availability of heating and cooling anywhere is that how right now buildings in the north or south look alike despite the fact that they are located in different climates. Buildings in hot climates such as Mumbai share similar technologies with ones located in cold climates such as Boston or temperate climates such as London or Addis Ababa. But this has led to an increase in energy and material consumption, contributing to global warming and climate change. *Bioclimatic* design solutions—building strategies that respond to regional climate(U.S. Green Building Council 2014)— will play a vital role in carbon reduction efforts and will have to be implemented in sync with advances in building technology.

By making reliable bioclimatic information easily available early in the design process, this research aims to make simple, sustainable design solutions accessible to building designers, and virtually anyone interested in improving their homes, all around the world. Empowering architecture to take a leading role in reducing carbon emissions calls for an evolution of design attitude among professionals, where the highest attention shall be given to climate and carbon.

Chapter 2 - Background

2.1. Urbanization and the future of buildings

Worldwide, cities are expanding and the growth rate is different in different parts of the world. We need to specifically focus on areas with the highest growth rates namely Asia and Africa. According to the UN World Urbanization Prospects report, more than two-third of the world population is expected to live in cities by 2050 and urban population in emerging economies will double (UN DESA 2018). As illustrated in the figure below, from a recent paper entitled *Building for zero, the grand challenge of architecture without carbon* (Weber, Mueller, and Reinhart 2021), the largest demand for new construction will be in the majority world with emerging economies: total floor area is expected to grow four-fold in India and more than double in African countries.

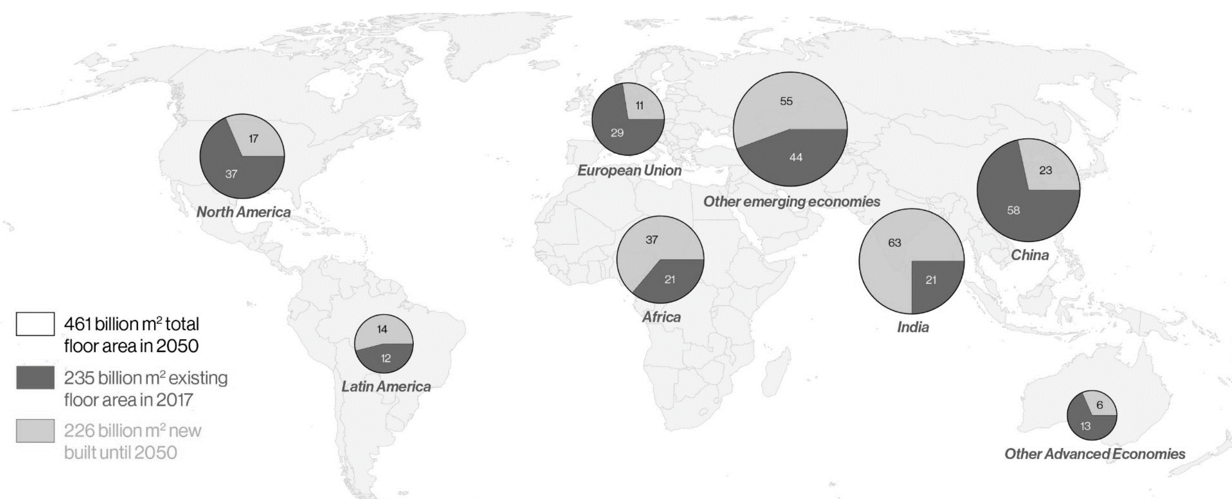


Figure 2.1-1 The building stock will double until 2050 and 68% of world population will leave in cities

Growing energy demand

With economic growth and increasing outdoor temperatures due to global warming, mechanical conditioning systems in buildings that require large amounts of energy are becoming the norm. According to the International Energy Agency (IEA), for example, 90% of homes in the US have air conditioning (AC), where the market for AC units is at a point of saturation (U.S. Energy Information Administration (EIA) n.d.). In China, outpacing every country by far in AC use, 60% of homes have AC units. In India, where AC units were previously rare, energy consumed for cooling increased 15-fold since 1990, and yet, only 5% of homes have AC installed. An additional challenge in the case of India and other hot-humid climates such as Bangladesh is high outside air pollution that causes serious health problems and premature deaths, resulting in a growing demand for air-filtration and purification systems. In most African countries, where strict energy standards are lacking, a flood of imported AC units that are old and inefficient are driving up energy consumption and greenhouse gas emissions. Electricity demand for residential AC units is on track to jump 10-fold across Africa by 2040(Fleming 2020; Charts - Data & Statistics IEA 2021). Globally, air conditioning uses roughly 10% of all electricity consumed per year, and the IEA predicts that it could triple by 2050 if it continues unchecked, proving disastrous for global emissions and making 2050 climate goals difficult to achieve.

Growing demand for a skilled workforce

There is an immediate demand in the building sector to house a growing world population with a global shortage of adequately trained designers and architects. Studies show that in India, unskilled construction workers are about 83% of the total construction work force(Ramana and Nallathiga 2013). And the U.S. is expected to need about 0.8 million more employees by 2028 (Bureau of Labor Statistics 2019). As the global building stock will double by 2050, making education on sustainable building design methodologies available for workers in the design construction industry in any part of the world is very important for energy and carbon reduction.

There are ongoing efforts globally to improve design education with the goal of enabling future architects to mitigate climate change. Some architecture schools have proposed new pedagogical methods for architectural studios to equip students with the skills to design carbon-neutral buildings (Passe 2020). In the United States, for example, the National Architectural Accrediting Board (NAAB) revised the conditions for accreditation in 2020 requiring programs to instill in students a holistic understanding of the dynamic between built and natural environments (Architectural Accrediting Board 2020). However, the question remains whether academia will be able to respond fast enough to the urgent imperative for carbon reduction.

2.2. Bioclimatic design toward hybrid buildings

Over the course of centuries, builders around the world had refined different types of bioclimatic architecture, and much of the world’s architecture, prior to the 20th century, responded to the regional climate. Before the invention and widespread use of air conditioning technology, a *bioclimatic* design approach that relied on passive strategies and vernacular construction was the norm. People opened windows to bring in fresh air and cool their buildings. Local materials with good thermal properties were used for building facades to prevent heat loss when it is cold. And breathing, earth walls were used to keep spaces cool when it is hot. However, in the name of technological advancement, we have gotten away from all of that.

The premise of *bioclimatic* design is that buildings utilize natural heating, cooling, and daylighting, and it had been promoted in a series of professional and popular publications in the

1950's and 70's(Fitch and Siple 1953; Olgay and Olgay 1957; Givoni 1976; Milne and Givoni 1976). However, contemporary design practice has gotten away from it since the widespread use of air conditioning and electric lighting.

Bioclimatic architecture not only plays an important role in reducing dependence on fossil fuels, but also maximizing indoor comfort and well-being. One of the primary goals of a sustainable building design is to provide comfortable, healthy spaces for occupants. There is ample research that outlines the influence of thermal environment on occupants' comfort, well-being and their productivity (Kaushik et al. 2020). With climate change and the accompanying rising temperatures, it is likely that today's naturally ventilated and mechanically heated spaces will need active cooling at some point in the future. This requires designers and green building consultants to implement sustainable building solutions for a changing climate that creatively integrate passive and active building strategies.

Low-energy building strategies and modeling methods

One of the bioclimatic design strategies that has long been used to create acceptable comfort conditions in buildings is natural ventilation. Even though relying only on natural ventilation is not possible in many climates, every climate offers an opportunity for natural conditioning at least for few weeks or months during the year. This kind of approach to use natural ventilation whenever possible could significantly reduce cooling energy in hybrid buildings. For example, according to a study of 76 cities in China, 8 – 78% of the cooling energy consumption can be potentially reduced by natural ventilation(Tong et al. 2016). Globally, hybrid ventilation can provide large energy savings (over 50%) and high levels of indoor air quality(Kim et al. 2019).

Hybrid buildings, also known as mixed-mode buildings, employ a hybrid approach to space conditioning that combines operable windows and mechanical cooling. A well-designed hybrid building can be more comfortable and use less energy by taking the advantage of the strengths of both systems ((Brager, Arens, and Lehrer 2022)). To support the design of hybrid buildings, there is a need for a reliable bioclimatic information that is easily accessible and can be used earlier in the design phase. This is particularly important because the most critical design decisions determining the effectiveness of natural ventilation and building performance, such as massing, opening size and programmatic arrangement, are typically made at an early design phase.

2.3. Massive Open Online Courses (MOOCs)

Enabled by widespread access to the internet in many parts of the world and driven by a need for skilled workers, the fast growth of online education has become a global phenomenon (Kumar et al. 2017). According to a 2015 study on online education, the first correspondence courses began in the 1800's using parcel post to reach students (Kentnor 2015). By 1900s distance education took to the radio waves, and soon after expanded though the invention of television. Online learning emerged in 1982 at a management school in California, and by the end of 1990s more online courses were founded including the program at the University of Phoenix, and New York University Online (Mellieon 2014).

MOOCs are one category of online distance courses, available for unlimited number of participants, enabling them to learn at their own pace. MOOCs play a role in advancing education by providing a platform where higher education institutions can interact with learners using their courses that are hosted online. To date, studies show that various online education platforms have enrolled several million students, numbers which are rarely heard off within the context of higher education. In contrast to traditional education, MOOCs are not limited by the physical size of class rooms, tuition fees and admission procedures to enroll.

Enrollments in MOOCS

The recent increase in popularity of MOOCs, distributed in platforms such as Udacity, Coursera and edX, has made it possible for anyone with an internet connection to enroll in free, university level courses (Piech et al. 2013). MITx is the massive open online courses program at MIT, that produces over 3000 MOOCs from MIT departments and faculty, for over 39 million learners worldwide . Enrollment is a key measure, and a necessary step to pursue learning on a MOOC platform, but it is not by definition a learning outcome (Jacqmin 2021).

According to a study on a French MOOC platform called FUN, characteristics related to course, teacher and institution influence the enrollment decision of students, where enrollment is open to all learners. Coverage from social and traditional media around the course, the language of instruction, and estimated amount of work needed to complete the course are identified as key drivers (Jacqmin 2021). The study noted that preferences of national and of international students tend to differ on several dimensions, including the language of instruction and the starting time of the course. For the courses in the French platform April tend to attract significantly more students, and those in June and September significantly less students.

How do other externalities affect enrollment? The case of the MITx course, AP Biology, on edX by Katie B. and Mary Ellen W. (eMOOCs 2021) has been administered in the past 6 years, with thousands of learners. For course runs administered during the covid lockdown, the authors showed that enrollments significantly increased but not number of certifications. In this particularly example, retention rate of verified learners was smaller – less than 5%. Repeats were a common scenario, where many learners retaking the course to get a certificate is recorded. Additionally, there were many learners participating from MIT, who registered for the course with their MIT email account. Because the course was considered as a pre-requisite for other MIT residential courses, in house participation was large. This indicated that global reach might have not been the goal of this MOOC course.

Computer-assisted delivery and assessments

An opportunity for online education lies in advancements in computer science and educational data-mining that can be leveraged to improve online content delivery and customize e-learners experience. Studies presented at the *International Conference on Computers in Education* have been proposing promising tools and e-learning systems (Zaïane 2002). For example, a study proposed a recommender system that tries to "intelligently" recommend actions to a learner based on the actions of previous learners. Using integrated web-mining techniques, the recommender agent software improves course material navigation to assist the online learning process. A more recent study published in the journal *Education and Information Technologies* (2021) proposed an approach to predict learner's performance through video-sequences viewing-behavior using education data mining. The study analyzed the path followed by a learner watching a lecture video, and the way the learner navigates the pedagogical sequences of the content, in order to predict whether a learner can pass or fail the course, with a predication accuracy of 65% (el Aouifi et al. 2021). This method may help an online teaching team understand learners' engagement and apply it for early, effective guidance to learners who need assistance.

To date there are relatively few MOOCs on the topic of architectural design. One of the challenges of delivering massive open online courses with open-ended assignments is implementing assessment methodologies that can scale up. In contrast to science and math classes that can effectively rely on computer grading, courses in humanities, social sciences, and design with complex, open-ended assignments, traditionally rely on expert evaluations to deliver feedback to learners. However, in courses with tens or hundreds of thousands of enrollments, it would be impossible to have enough human experts to grade assignments, and peer grading is instead employed. Despite promising initial trials, peer evaluations do not always deliver accurate results compared to human experts (Piech et al. 2013).

Peer assessments had long been used in the traditional classrooms of colleges and universities, getting large traction before the proliferation of online education in the past two decades. Researches in the ’90s indicated that peer evaluation is of adequate reliability and validity, and peer assessments of writing, and assessments using grades and tests have shown positive formative effects on student achievement and attitude(Topping 1998). The study also pointed out that computer-assisted peer assessment is an emerging growth area. In more recent years online education platforms such as Coursera are implementing calibrated, statistical models to significantly improve the efficacy of peer assessments(Piech et al. 2013). By developing algorithms for estimating and correcting for grader biases and reliabilities, their approach showed significant improvement in peer grading accuracy on real data with over 63,000 peer grades from Coursera’s course offerings. In a different study, De Marsico et al proposed methodologies to leverage Conditional Probability Tables (CPTs) in a Bayesian approach to grade open ended answers (de Marsico, Sterbini, and Temperini 2017).

How far can technology take online education?

The primary challenge of online education lies in the quality of content delivery for millions of online learners enrolled every year in a myriad of courses across platforms. To what extent can the current online education system be supported by means of new technologies and advanced knowledge in computer science to better respond to global challenges? Beyond challenges faced in a traditional classroom, studies have shown that having the right digital tools and methodologies to foster learners’ engagement in the absence of an in-person guidance is critical. Providing personalized guidance and feedback to learners, especially when computer evaluations are not possible due to the subjective nature of courses such as the MOOC course presented in this thesis, is a limiting factor in scaling up some online courses. Following the much-publicized experiments launched at elite universities and in elementary schools in the poorest neighborhoods in the US, 2012 was declared the “year of the MOOC” in the New York Times. However, about a decade later, challenges associated with educational technologies, such as using auto-graders and computerized “intelligent tutors”, are still bedeviling educators.

The question *how far* also implies geographic reach and equity of education. What is exciting about online education is that, in a highly networked global society, it holds the promise to improve accessibility of education to communities with limited resources, especially those in the developing world. Proponents of large-scale learning have boldly promised that technology can disrupt traditional approaches to schooling, radically accelerating learning and democratizing education (Reich 2020). However, other studies on online education have raised concerns that online learning can contribute to educational inequality. Justin Reich, in his article *Failure to Disrupt: Why Technology Alone Can’t Transform Education*, argues that learning technologies—

even those that are free to access—often provide the greatest benefit to affluent students and do little to combat growing inequalities in education. Another study using data from 68 MOOCs offered by Harvard and MIT between 2012 and 2014 raise concerns that MOOCs and similar approaches to online learning can exacerbate rather than reduce disparities in educational outcomes related to socioeconomic status (Hansen and Reich 2015). In their analysis the authors found that course participants from the United States tended to live in more affluent and better-educated neighborhoods than the average U.S. resident.

Chapter 3 - Challenges and Opportunities

3.1 Problem statement

Limitations of available methodologies for bioclimatic design

One of the major driving forces for the global cooling boom is the implementation of energy inefficient solutions, such as installation of old and inexpensive AC units, by building owners to maintain indoor comfort in a warming climate. A hybrid, *bioclimatic* design and technological approach that utilizes passive strategies whenever possible will play a crucial role in reducing the energy needed to keep buildings comfortable.

A commonly used methodology to understand the potential of a given climate at the beginning of a design project and to provide preliminary suggestions on potential passive building strategies is a climate-file based approach. This method is a good starting point by evaluating outdoor conditions such as ambient temperature and humidity; however, it does not account for building parameters such as envelope performance, thermal mass and internal loads that decisively influence indoor conditions.

Other design methodologies to evaluate various building strategies use detailed building simulations and require users to set up an energy model. One of the widely used numerical simulation tools is EnergyPlus, an engine developed by the U.S. Department of Energy (DOE). The engine outputs results on indoor temperature, humidity levels and energy loads by implementing a heat balance equation on a zone air (EnergyPlus 2016). It has been implemented in various 3-D graphical design modeling environments that are user-friendly. For example, ClimateStudio is a plugin for the Rhinoceros and Grasshopper Computer Aided Design (CAD) software, while DesignBuilder is a stand-alone application created to simplify EnergyPlus thermal simulation. However, their application during the schematic design stage is limited due to the complexity of the required inputs and the level of geometrical information required when setting up the thermal model.

To effectively support the design of sustainable building strategies at an early-design stage, there is a need for an alternative approach that is easily accessible and can be used when only limited information about the project is available such as the location and building program. Such an approach could make sustainable building design guidelines more accessible to consultants, building owners and educators worldwide who are committed to making low-carbon buildings.

Sustainable building design education from traditional classrooms to e-platforms

The opportunity offered by online education in sustainable building to create a global cadre of architects and builders who are quipped to design low-carbon and net-zero buildings design is yet untapped. Delivering a sustainable design course online requires tuning content delivery and course assessment methodologies used in the traditional class room to online learners. As presented in the background section *Computer-assisted delivery and assessments*, there is a growing body of literature on the delivery and performance assessments of MOOCs, particularity those with complex, and open-ended assignments, that have tens or hundreds of thousands of learners. Such MOOCs include courses in humanities and social sciences, where open-ended assignments are usually in writing. This study identified two important aspects that are missing in the current state-of-arts.

First, to the author's knowledge, systematic studies on the delivery and assessment of online design courses that highly credit 'originality' and quality of presentation, and implement group projects and critics as a tool are not available. Architecture and design courses prove to be challenging to teach online asynchronously, because most of its content delivery relies on direct engagement, and live discussions between learners and instructors.

Second, the effectiveness of peer assessment for online education has been studied and greatly improved using statistical models based on what is called a large consensus of peers, but not expert evaluations. By taking a closer look to selected projects that are both peer and expert graded, the study provides recommendation for improving peer-assessments in a sustainable building design course.

3.2 Thesis objective

As a framework of this thesis, I present the following hypotheses pertaining to the feasibility and relevance of such an approach.

> It is **technically feasible** to teach actionable sustainable building strategies for a global audience, including learners who do not have any design or construction background, by making reliable bioclimatic information available in a clear and intuitive format.

> A **web-app that relies on simplified simulation** would be able to answer a highly relevant, recurring suite of climate questions to guide design processes at the beginning of a project.

Guided by these ideas, the thesis makes two main contributions to the field of sustainable building design and education. First, an early-design web-application called *ClimaPlus* is developed and validated, with the goal of making *bioclimatic* building strategies accessible to consultants, architects and building educators. The goal is not to reinvent well developed simulation engines such as EnergyPlus, but rather to provide instant feedback on the potential of bioclimatic design concepts at an early design phase using a simplified building model. *ClimaPlus* can be operated through a web browser on a computer or a smart phone to conduct environmental performance analysis for a selected city and building program. Second, the web-app is being used extensively for high impact learning in a MOOC class, entitled *EdX 4.464x Sustainable Building Design* and was administered twice in 2020 with a total enrollment of over 40,000. I illustrate the important role the web-app played in teaching sustainable building design for a global audience by showcasing course projects that achieved ambitious performance goals by significantly reducing building energy-use. In the outlook section of this thesis, I will further use ClimaPlus as a global energy policy tool that can efficiently showcase the effectiveness of different technology adoption strategies in reducing carbon emissions in neighborhoods and cities.

3.3 Thesis outline

In the research work section, *Chapters 4* and *5* present the proposed early-design analytical approach and its validation, with the goal of providing reliable bioclimatic design recommendations at an early-design stage. The analytical model called *climabox* and its implementation in a web app ClimaPlus are presented in depth.

In *Chapters 6* delivery methodology and lessons earned from teaching a university-level sustainable building design course to thousands of leaners around the world are presented. This portion of the dissertation research pertains to the application of the web-app ClimaPlus in sustainable building design education. Surveys before, during and after the course are used to gather data to improve delivery methodology of the course, and the analysis is presented in Chapter 6.

The outlook section in the conclusion chapter, outlines other potential applications of the *climabox* approach that would be explored in future work. In addition to educational purposes, it can be applied to inform policies implemented to reduce carbon emissions of buildings, particularly in the developing world where the largest urban population growth is predicted.

Chapter 4 - Early-stage sustainable building design approach

This chapter presents the development of a web-application, called *ClimaPlus*, and its underlying analytical workflow. The web-application uses climate data for the project location and quick simulations of a single zone model that abstracts a building – a *climabox*. This web-app intends to bridge the gap between a quick, climate-file based analysis and a detailed building performance study using numerical tools such as EnergyPlus. The study has been partially presented and can be found in these references[1,2,3].

4.1. Climate [plus] analysis

As a first step of the methodology, hourly outdoor temperature and relative humidity values are evaluated to identify if natural ventilation is possible based on user-preferred comfort evaluation criteria. The data on outdoor conditions are extracted from EnergyPlus weather data files (EPW) that are publicly available for over 15,000 climates globally (US-DOE and NREL 2018; Crawley and et al 2020).

The figure below shows an example of outdoor condition analysis with an acceptable comfort range given strict set points for a project in Boston. The total number of hours that will

[1] **Arsano, A. Y.** (2020). Designing for Natural Ventilation: Climate, Architecture, System. In *The Materials Book*. Ilka Ruby & Andreas Ruby (Ed.). Berlin: Ruby Press.

[2] **Arsano, A. Y.**, & Reinhart, C. (2019). Early-Design Optimization of Target Ventilation Rates for Hybrid Buildings Using Single-Node Analytical Model. In *Proceedings of BS2019: 16th Conference of International Building Performance Simulation Association*.

[3] **Arsano, A. Y.**, & Reinhart, C. F. (2017). A Comparison of Methods for Evaluating Ventilation Cooling Potential Building Program Based Climate Analysis for Early Design Decisions. In *Proceedings of BS2017: 16th Conference of International Building Performance Simulation Association*.

meet both outdoor temperature (between 18 and 25 °C) and humidity (less than 70%) requirements are 974 hours.

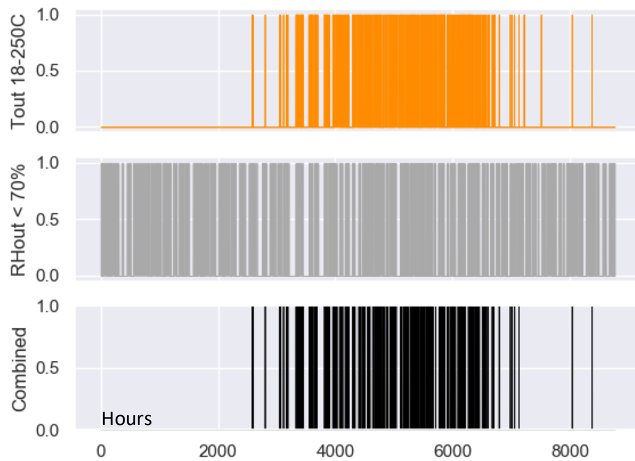


Figure 4.1-1 Hourly outdoor temperature and humidity that are within a strict comfort requirement in Boston

It is important to recognize that this outdoor temperature-based analysis is limited to characterizing a climate as hot-to-warm, temperate, or cold, rather than providing complete information on the availability of natural ventilation.

4.2. The *climabox* approach

Beyond climate-file based analysis discussed in section 4.1, the *climabox* approach further allows users to conduct a one-zone thermal analysis of a small building or part of a larger building including energy use for equipment, lighting, heating, and cooling. The adopted single-node analytical model uses simplified mathematical expressions to predict hourly indoor temperature for the non-geometric abstraction of a building based on outdoor temperature, thermal resistances of the envelope and openings, internal loads, and the thermal response of the zone.

The potential of passive conditioning in naturally ventilated and hybrid buildings can be significantly increased with an integrated application of different passive building strategies, such as thermal mass and night ventilation. Detailed discussions of the different building parameters and modes of operation that can be evaluated with the climabox approach are presented in the following sections.

To measure occupants' comfort in partially conditioned and naturally ventilated spaces, the number of hours that are above and below user-defined temperature thresholds is reported on an hourly indoor/outdoor temperature chart.

Supported design interventions include window layout, envelope insulation levels, and internal loads management. Apart from energy use, outputs include operational energy costs and carbon dioxide emissions. The goal is to enable the user to formulate early-stage design guidelines at the beginning of a design project.

4.2.1. Climabox: a non-geometric abstraction of a building and internal loads

The climabox represents a building, an office, or a residential unit, using a single zone with adjustable width, length, and height. The glazing area on the south, east, west, and north facades can be defined with window-to-wall ratios ranging from no window to 90% of the respective façade areas.

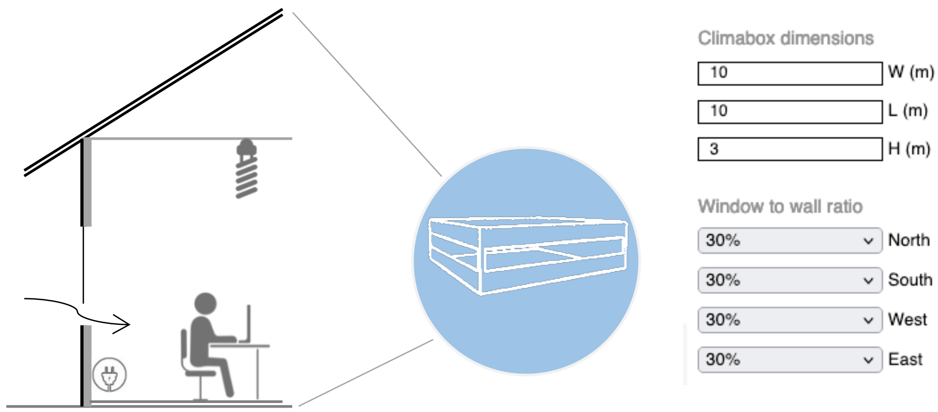


Figure 4.2-1 Climabox: a non-geometric abstraction of a building and internal loads

Form abstraction

Wall and glazing areas of the climabox are inputs in the analytical model discussed below to calculate conduction losses and solar gain to the zone. Here, two approaches are presented that can be used for the abstraction of a building into a *climabox:* the shoebox and compactness factor (CF). With either of these two methods, a single zone can be defined with the required dimensions as shown in the figure below.

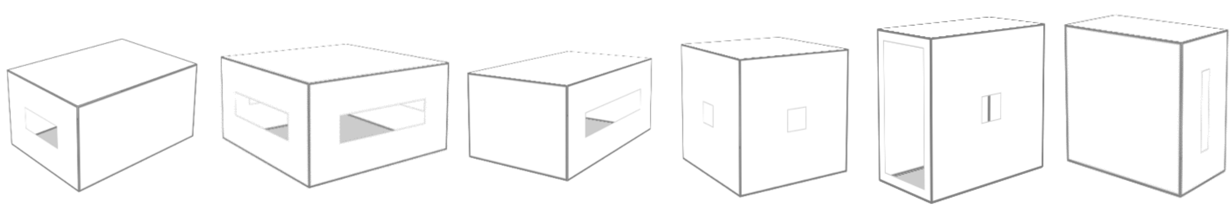


Figure 4.2-2 Examples of climabox abstractions of a zone, with different length, width, and height, glazing area and orientation

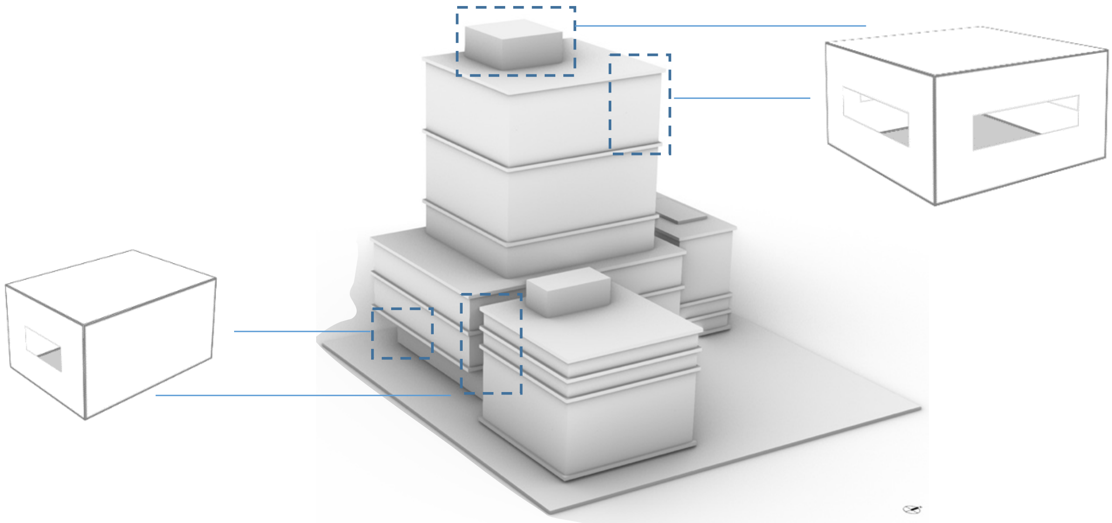


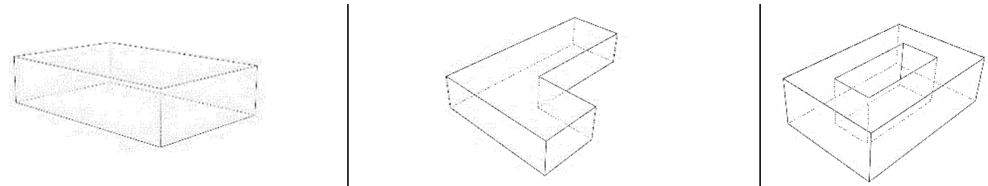
Figure 4.2-3 climabox as an abstraction of parts of a building in the shoebox approach

In the shoebox approach, part of the building being studied is abstracted into the single zone climabox, as shown in Figure 4.2-3 . In the compactness factor approach, the building's façade area, floor area, and roof area are used to calculate the compactness factor, which can then be translated into the length, width, and height dimensions of the climabox. A compactness factor represents the ratio of the total occupied floor area and exposed building surface area – façade and roof.

A comparison of different design typologies with similar total floor area using a *compactness factor* provides useful information about the massing of the project. A low compactness factor indicates that the building has relatively smaller building depth and a large exposed surface, while a high compactness factor indicates that the building has deep floor plans potentially limiting indoor airflow but significantly reducing heat conduction losses through building envelope.

Furthermore, the total area of exposed external surfaces that is one of the inputs in the single-node analytical model can be calculated from the *compactness factor.* It is an important parameter because conduction heat losses of the building to the external environment take place through these external surfaces.

To illustrate the application of the *compactness factor* three variants for a hypothetical medium-sized office building are shown in figure below based on the *U.S. DOE Commercial Reference Building Models of the National Building Stock* database. Furthermore, the data in standard ASHRAE 209 (ASHRAE 2018) provides representative parameters for various building types when the rough building form has not been prescribed. The medium office building that is being used as an example has a total floor area of 4982 m^2 and a glazing fraction of 0.33.



Base building (medium office)	Variant 1: with 12% lower CF	Variant 2: with 48% lower CF
A_{facade}:1972 m^2	A_{facade}: 2448 m^2	A_{facade}:5641 m^2
$A_{perfloor}$: 1660 m^2 (3 floors)	$A_{perfloor}$: 1650 m^2 (3 floors)	$A_{perfloor}$: 1260 m^2 (4 floors)
A_{roof}: 1660 m^2	A_{roof}: 1650 m^2	A_{roof}: 1260 m^2
Compactness factor: 1.38	Compactness factor: 1.20	Compactness factor: 0.72

Figure 4.2-4 Three massing prototypes representing medium office floor area based on DOE reference building

Envelope properties

Internal loads

Non-geometric features of the climabox include internal loads from occupants, lighting, and plug loads. Heating and cooling systems with varying costs and emissions are also defined based on their sources of energy: natural gas or electricity. The standard ASHRAE 90.1 (ASHRAE 2013) is used as a reference to define occupancy schedules, lighting and equipment loads of a representative office building.

4.2.2. The analytical model

A simplified RC model, shown below, represents the *climabox* with mathematical expressions representing the different building parameters. These expressions are integrated into an analytical model given in *Eq 4.2-1*.

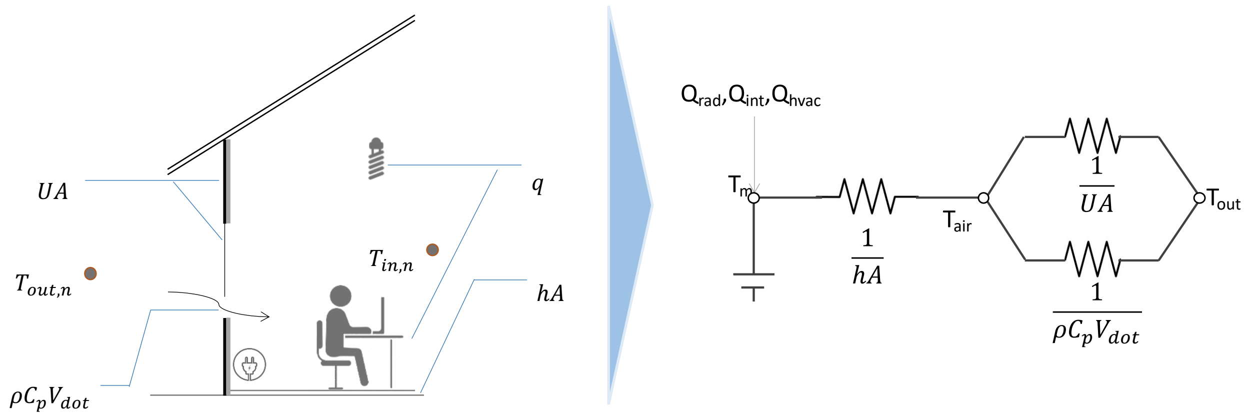


Figure 4.2-5 A sketch diagram showing the representation of the climabox model into an RC model.

Conduction, ventilation, convection from thermal mass, and solar and internal loads are represented mathematically.

$$\boldsymbol{T_{m,n+1}} = \left(\left(\frac{\mathbf{1}}{(\boldsymbol{UA} + \boldsymbol{\rho C_p V_{dot}})} + \frac{\mathbf{1}}{\boldsymbol{hA}}\right)\boldsymbol{q}_{rad,\,int,\,n} + \boldsymbol{T_{out,n}}\right)\left(\mathbf{1} - \boldsymbol{e}^{\frac{-1}{\tau}}\right) + \left(\boldsymbol{T_{m,n}} * \boldsymbol{e}^{\frac{-1}{\tau}}\right) \qquad \text{(Eq 4.2-1)}$$

Where:

$\frac{1}{UA}$ *is conduction resistance of the envelope*

$\frac{1}{\rho C_p V_{dot}}$ *is resistance due to infiltration and ventilation*

$\frac{1}{hA}$ *is the convective resistance at the thermal mass surface*

τ *is the thermal time constant*

$q_{rad,\,n}$ *represents heat loads from solar radiation at the simulation hour*

$q_{int,\,n}$ *is the internal heat load from occupants, lighting, and equipment at the simulation hour*

T_{out} *is the outdoor air temperature*

T_m *is the temperature of the thermal mass*

It is important to note that the $T_{m,n+1}$ in this analytical approach represents the temperature of the thermal mass. The following equation is used to calculate T_{air} using weighted/average voltage approach, using thermal mass temperature calculated in *Eq 4.2-1*.

$$T_{air} = \frac{hATm + (UA + \rho C_p V_{dot})Tout}{hA + UA + \rho C_p V_{dot}} \quad \text{(Eq 4.2-2)}$$

Where:
UA is conduction through the envelope
$\rho C_p V_{dot}$ is the rate of convective heat loss from ventilation
hA is the rate of convective heat transfer from the thermal mass surface
$Tout$ is the outdoor air temperature
Tm is the temperature of the thermal mass

Conduction though the envelope

Four inputs are available to define thermal resistance of opaque and glazing surfaces: U-values for roof, wall, floor, and glazing. The total *UA* value of the *climabox* is calculated by multiplying the U-value of the different surfaces with their corresponding surface areas.

Solar radiation through glazing (q_{rad})

The approach uses a simplified glazing model using a *simple glazing* module with only U-value and SHGC. As presented in EnergyPlus Documentation, the Engineering reference (page 293), such a simplified approach in building simulation software is just an approximation. This is due primarily to the following factors (EnergyPlus 2016):

- SHGC combines directly transmitted solar radiation and radiation absorbed by the glass which flows inward. These have different implications for space heating/cooling. Different windows with the same SHGC often have different ratios of transmitted to absorbed solar radiation.
- SHGC is determined at normal incidence; angular properties of glazing vary with number of layers, tints, coatings. Products with the same SHGC, can have different angular properties.
- Window U-factors vary with temperatures.

The *pvLib* library is used to identify radiation on various surfaces from hourly weather data. Angle of Incidence (AOI) dependent correction coefficients are calculated to adjust solar gain though the simple glazing based on the solar gain ratio of EnergyPlus and the climabox approach.

Ventilation rate prediction

Natural ventilation by wind and stack or buoyancy with open area is calculated using analytical equations provided in EnergyPlus Input Output reference (US Department of Energy 2015). The predicted ventilation air flow rate (m3/s) is used to calculate convective heat-lose due to wind and buoyancy driven ventilations, as shown below.

$$q_{conv} = \boldsymbol{\rho C_p V_{dot}}(T_{\boldsymbol{a}} - T_{\boldsymbol{out}}) \qquad \text{(Eq 4.2-3)}$$

Where:

$q_{\boldsymbol{conv}}$ *is the convective heat transfer due to ventilation in kW*

ρ *is the density of indoor air (1.225 kg/m3)*

C_p *is the specific heat capacity of air (1.0 kJ/kg.K)*

V_{dot} *is the volumetric air flow rate of air due to ventilation in* m^3/s

$T_{\boldsymbol{a}}$ *is the indoor air temperature in K*

$T_{\boldsymbol{out}}$ *is the outdoor air temperature in K*

The *ZoneVentilation:WindandStackOpenArea* object implemented in EnergyPlus, is adopted in the climabox approach as it is intended for simplified ventilation calculations as opposed to the mode detailed ventilation investigation that can be performed with the *AirflowNetwork* model. According to *ZoneVentilation:WindandStackOpenArea* model, the ventilation airflow rate is a function of wind speed and thermal stack effect, along with the area of the opening being modeled. The ventilation flow rate is controlled by a multiplier fraction schedule applied to the opening area, and through the specification of minimum (T_{out_min}), maximum (T_{out_max}), and setpoint ($T_{in\_setpoint}$) temperatures.

The equation used to calculate the ventilation rate driven by wind, as shown in the equation below, is given by ASHRAE Handbook of Fundamentals, Equation 37 in Chapter 16 (ASHRAE Standard 2017). Hourly wind speed and velocity are calculated using weather file data for the selected location.

$$V_{dot\text{-}wind} = \boldsymbol{C}_w A_{opening} \boldsymbol{F}_{schedule} \boldsymbol{V} \qquad \text{(Eq 4.2-4)}$$

Where:

$\boldsymbol{V}_{dot-wind}$ is wind driven volumetric air flow rate in m^3/s

$\boldsymbol{C}_w$ is opening effectiveness, dimensionless

$A_{opening}$ is opening area in m^2

$\boldsymbol{F}_{schedule}$ is open area fraction, dimensionless user-defined schedule value
$\boldsymbol{V}$ is local wind speed in m/s

The opening effectiveness is auto-calculated for each time step based on the angle between the actual wind direction and the *EffectiveAngle*, the angle in degrees between the North and the opening outward normal (Ummethours 2016), using the following equation:

$$\boldsymbol{C}_w = 0.55 - \frac{|EffectiveAngle - WindDirection|}{180} * 0.25 \qquad \textit{(Eq 4.2-5)}$$

The equation used for calculating the ventilation rate due to the buoyancy effect is also given in the ASHRAE Handbook of Fundamentals, by Equation 38 in Chapter 16. It is implemented in the climabox approach, as shown below.

$$V_{dot-buoyancy} = \boldsymbol{C}_D \boldsymbol{A}_{opening} \boldsymbol{F}_{schedule} \sqrt{2g\Delta H_{NPL}(|T_a - T_{out}|/T_a)} \qquad \textit{(Eq 4.2-6)}$$

Where:

$\boldsymbol{V}_{dot-buoyancy}$ is volumetric flow rate due to stack effect in m^3/s
$\boldsymbol{C}_D$ is discharge coefficient for opening, dimensionless
$\boldsymbol{A}_{opening}$ is an opening area in m^2
$\boldsymbol{F}_{schedule}$ is open area fraction, dimensionless user-defined schedule value
ΔH_{NPL} is the height from the midpoint of the lower opening to the neutral pressure level in m
$T_{\boldsymbol{a}}$ is the indoor air temperature in K
$T_{\boldsymbol{out}}$ is the outdoor air dry-bulb temperature in K

Hourly values for discharge coefficient for opening in the above equation is calculated as provided in ASHRAE Handbook of Fundamentals, by Equation 39 in Chapter 16:

$$\boldsymbol{C}_D = 0.40 + 0.0045 * |T_a - T_{out}| \qquad \textit{(Eq 4.2-7)}$$

Finally, the total ventilation rate is the quadrature sum of the wind and buoyancy air flows calculated using (Eq 4.2-4) and (Eq 4.2-6).

$$V_{dot} = \sqrt{{V_{wind}}^2 + {V_{dot-buoyancy}}^2} \qquad \textit{(Eq 4.2-8)}$$

Thermal mass

Convective heat transfer from thermal mass depends on the thermal mass area and thickness, as well as the convective heat transfer coefficient. Thermal time constant (hr) for the climabox zone

$$\tau = RC \qquad \text{(Eq 4.2-9)}$$

Where:

- R is the envelope resistance
- C is the thermal capacitance of the thermal mass in the climabox

The time-constant that represents the thermal response of the zone in a lumped variable τ is calculated as shown in *(Eq 4.2-9)* where: R is the total resistance and C is the thermal capacitance of the thermal mass as a product of mass (*m* in *kg*) and heat capacity of the material (*c* in *J/kg.K*).

$$R = \left(\frac{1}{\left(UA + \rho C_p V_{dot} \right)} + \frac{1}{hA} \right) \qquad \text{(Eq 4.2-10)}$$

The conduction resistance of the zone's envelope and ventilation airflow, and convection resistance of the exposed thermal mass surface is given in (Eq 4.2-10).

Where:

- U is the thermal transmittance of the building envelope in W/m^2K
- ρ is the density of air
- c_p is specific heat capacity of air
- V_{dot} is the volumetric flowrate of air
- h is the convection coefficient inside the zone
- A is the area of exposed thermal mass

Heating and cooling loads

For a conditioned zone, which could be in hybrid operation mode or fully conditioned, an additional step is used to predict the amount of heat energy that should be added or removed from the zone air to meet heating and cooling setpoints. With a heat balance equation at the air node or center of the climabox (*Figure 4.2-5*), where the heat capacitance of the air is approximated to be zero, we calculate the amount of heating or cooling energy to bring the air temperature to the heating or cooling setpoint temperatures respectively. *(Eq 4.2-11)* is a heat balance equation at the air-node for a free-floating building without any active heating or cooling, and *(Eq 4.2-12)* is a heat balance equation at the air-node to calculate heating and cooling loads required to maintain indoor air temperature at setpoint temperatures.

$$0 = \frac{T_m - T_{air}}{\frac{1}{hA}} + \frac{T_{out} - T_{air}}{\frac{1}{UA + \delta c_p V_{dot}}} \qquad \text{(Eq 4.2-11)}$$

$$q_{hvac} = \frac{T_m - T_{setpoint}}{\frac{1}{hA}} + \frac{T_{out} - T_{setpoint}}{\frac{1}{UA + \delta c_p V_{dot}}} \qquad \text{(Eq 4.2-12)}$$

In hybrid and fully-conditioned scenarios, the resistance from infiltration and ventilation will be a smaller value in comparison to a free-floating scenario, because we assume windows will be closed and the only source of outside air flow is infiltration.

4.2.3. The web-app, and the computational framework

The *climabox* engine is made accessible for any user with the web-app ClimaPlus, that is hosted online using AWS cloud services(Amazon Web Services (AWS) 2021), and developed using the python-based flask framework (Welcome to Flask 2010). The proposed computational framework at the backend of the web-app is showing in the following figure.

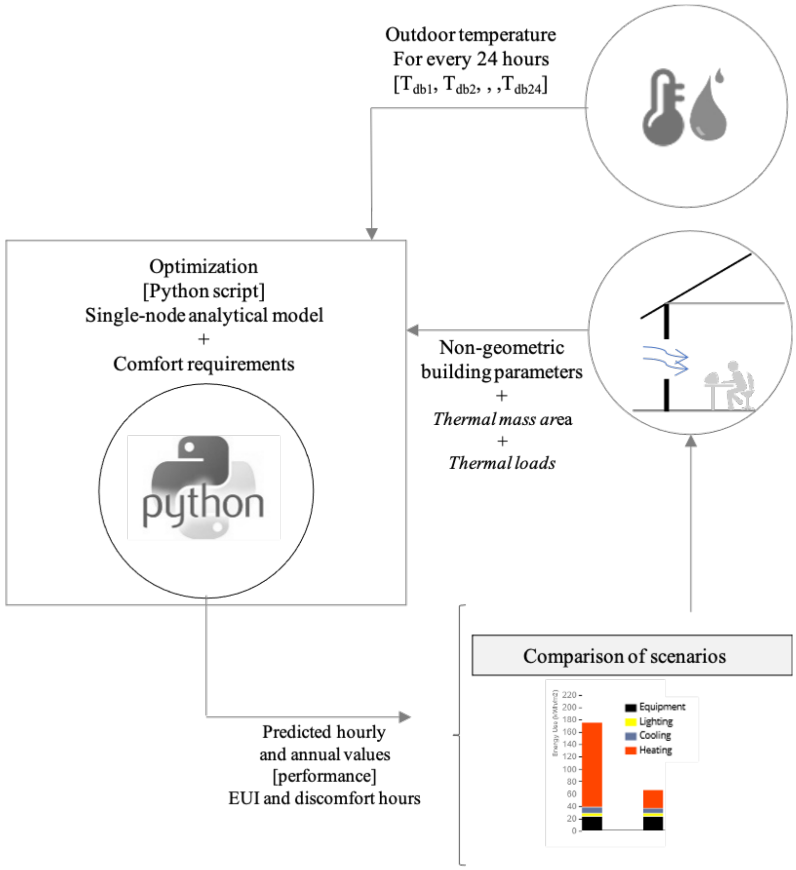


Figure 4.2-6 The proposed framework to evaluate different combinations of design variants and draw actionable design recommendations that maximize the effectiveness of bioclimatic building strategies.

ClimaPlus has been used to teach the MOOC course on sustainable building design with thousands of enrollees from different parts of the world, who followed the course track that offers learners to use publicly accessible and easy-to-use web-apps. More discussion is presented on the delivery of the course and the different tracks that are made available for learners in *Chapter 6: High Impact Teaching*.

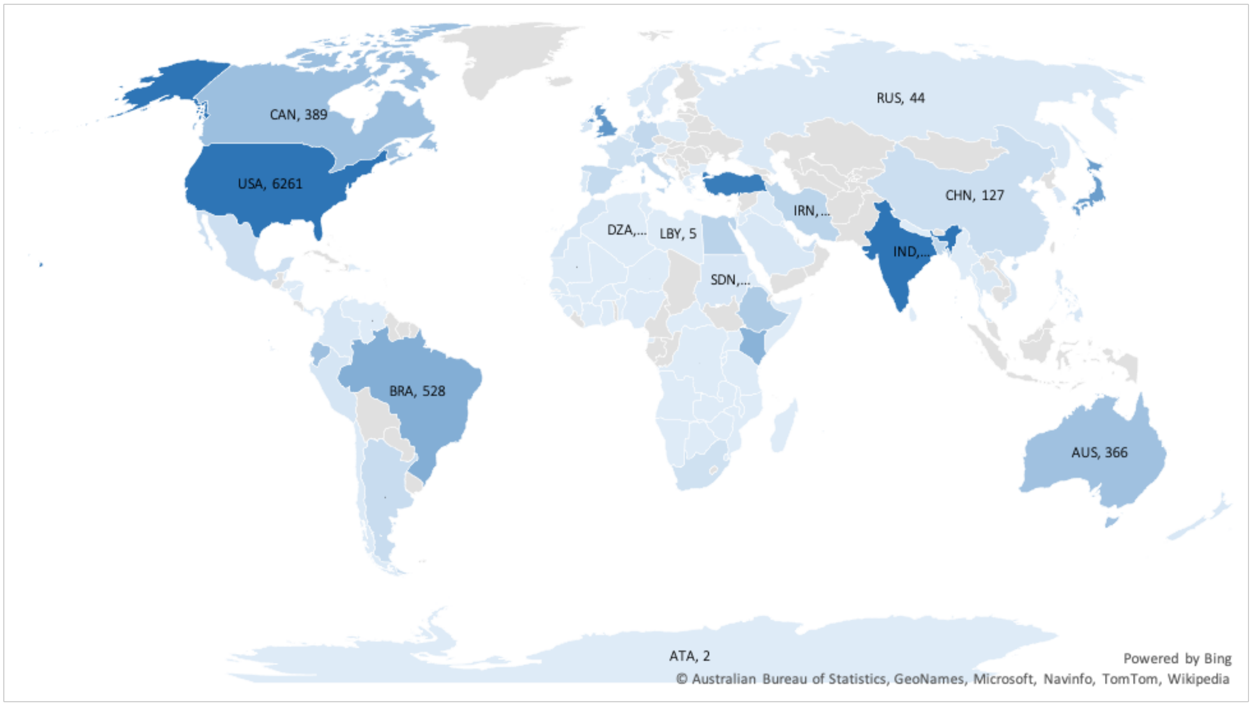


Figure 4.2-7 This map shows the number of times ClimaPlus has been used per country between Sept 2020 and Dec 2021

ClimaPlus has been used to study a climate over 17,000 times since the author started logging access data in Sept 2020. There are over 2,000 EPW weather files that are available directly on ClimaPlus. In the scenario, a user would like to use a different weather data in EPW format that is downloaded from commonly knows sources such as onebuidling.org (climate.onebuilding.org 2021).

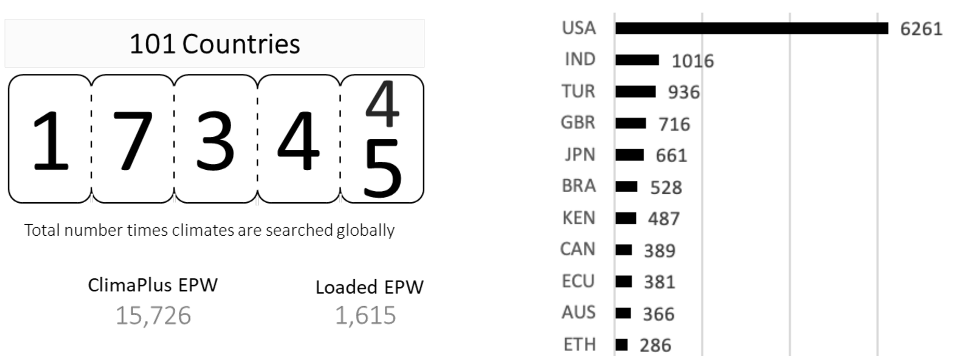


Figure 4.2-8 Number of times ClimaPlus has been accessed using available weather files in the app or loaded EPW files from other sources

4.3. Limitations of the climabox approach

Three main limitations of the *climabox* approach are summarized. First, the non-geometric abstraction of a building doesn't conclude partitions or interior sub-divisions, allowing the analysis of a single zone at a time. Similar to the a *shoeboxer* approach (Environmental Systems Lab 2020) that abstracts an arbitrary shaped building volume into a group of simplified generic perimeter and core floorplans, the climabox method only considers for heat gains and losses through external facades, while all surfaces between adjacent zones are considered to be adiabatic.

Second, cross ventilation across multiple openings is not considered because an airflow network model – a numerical method that can solve airflow induced by wind through multiple openings using certain convergence tolerance for acceptable state of equilibrium (EnergyPlus 2016) – is not integrated with the RC model. A simple arithmetic addition of predicted ventilation airflows from all opening, driven by wind as well as buoyance (*Eq 4.2-8*), is used to get the total ventilation airflow into the zone.

The third limitation is that indoor humidity levels are not considered at the current stage of the *climabox* model, hence energy use intensity and comfort hour predictions do not account for humidity limits. Considering humidity levels would be critical particularly for humid climates, affecting the potential of natural ventilation and hybrid modes of operation.

4.4. Conclusion

In conclusion, the high record of uses of the web-app shows its accessibility to explore a wide range of climates in different regions worldwide. The *climabox* simplified methodology with a small computational complexity delivered via any internet connected device can be used to answer key climatic and building design questions.

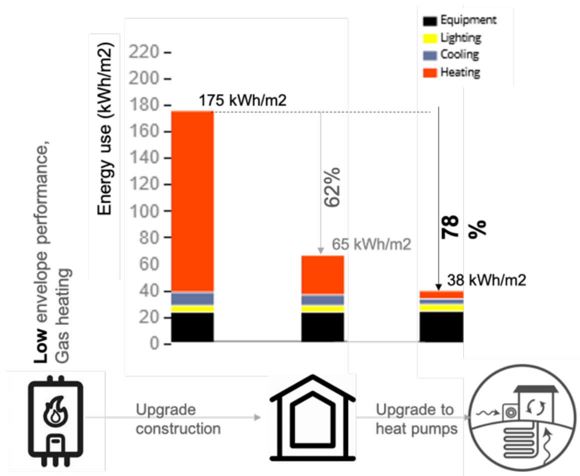


Figure 4.4-1 Exploration of building upgrading strategies for better energy saving

By making sustainable building design concepts accessible to a global audience, the approach plays a role in empowering designers or interested individuals to explore sustainable, *bioclimatic* building strategies based on climatic conditions of their location. This encourages the use of passive strategies as much as possible, promoting the design of hybrid buildings that combine recommended strategies to reduce energy use while maintaining occupants' comfort, such as natural ventilation, high performance envelopes, and efficient lighting and equipment.

Chapter 5 - Validation of the *climabox* model

The validation study aims to evaluate how well the *climabox* approach predicts the potential of natural ventilation and hybrid building strategies by comparing hourly and monthly simulations of an abstraction of a zone against EnergyPlus simulations. The validation study has two parts to compare the *climabox* approach against EnergyPlus: direct and pairwise comparisons. This chapter also reports the findings on the inconsistencies observed in the validation study and describe scenarios for a reliable application of the proposed approach.

5.1. Validation model

ANSI/ASHRAE Standard 140, *standard method for the evaluation of building energy analysis computer programs*, is Recommended test cases given in the standard include a fully conditioned base test (*case 600*), low mass test (cases 620, 640, 650), high mass test (cases 920, 940, 950), and free float test (cases 600FF, 650FF, 900FF, 950FF). A single zone geometry that is provided in the standard has a floor area of 48 m^2 and windows in the south façade with a total of 12 m^2. Based on this thermal model, a climabox is created in EnergyPlus information definition file (idf).

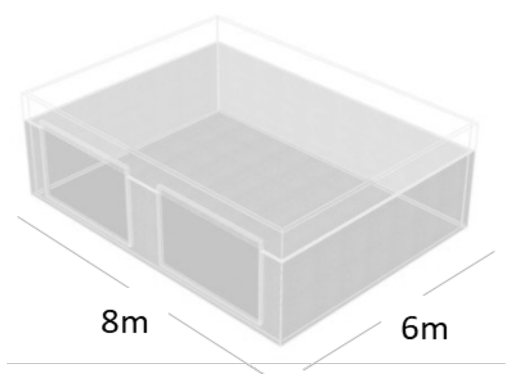


Figure 5.1-1 Geometric definition of the climabox used for the validation study

Denver, a dry cold climate, is the climate used in ASHRAE 140. In addition, two additional locations representing different climatic conditions are used for validation: Phoenix, a dry hot climate where cooling is the dominant energy load, and San Francisco, a temperate climate with a large potential for natural ventilation.

5.2. Direct comparison

5.2.1. Model inputs

Direct comparison of hourly model inputs in climabox vs EnergyPlus is conducted for different internal loads, solar heat gain through glazing, and ventilation/infiltration air flows.

Internal loads

Internal loads from occupants, lighting, and equipment (plug loads) are calculated based on the input schedules representing the building program and occupants' activities. By using same occupancy, lighting, and equipment schedules, a direct comparison of hourly internal loads calculated using the *climabox* approach and EnergyPlus showed similar results with a RMSE error of 0.05.

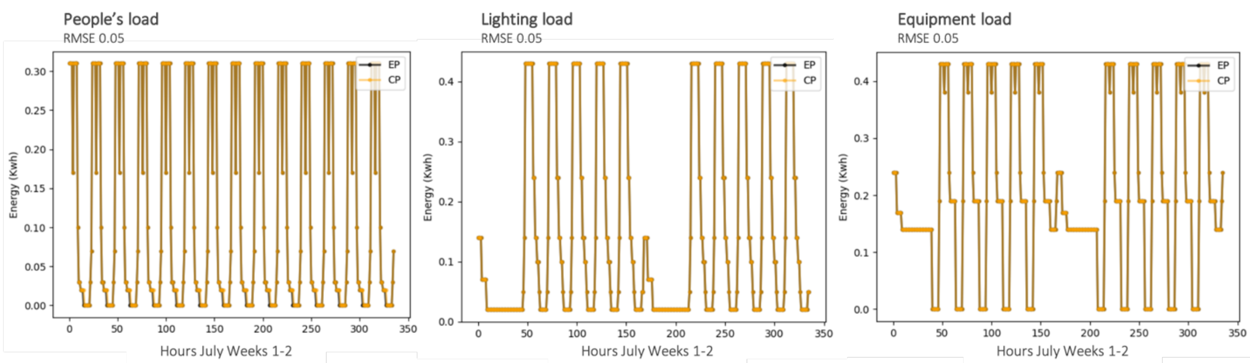


Figure 5.2-1 Direct comparison of internal loads in climabox and EnergyPlus

Heat gain through glazing from solar radiation

The primary difference between the *climabox* approach and EnergyPlus is the glazing model. A glazing in *climabox* is modeled analytically using a single U-value for thermal performance, solar heat gain coefficient (SHGC), orientation, and total area. On the other hand, the simple glazing model in EnergyPlus has incident angle dependent SHGCs. As shown in Figure 5.2-2, there is significant different between the hourly soar radiation predicted using non-angle dependent SHGC in *climabox* and incident angle dependent SHGC in EnergyPlus. To adjust for this difference between climabox and EnegyPlus, adjustment factors are calculated that are used as multipliers of the single SHGC value in climabox. The factors are used to adjust the solar heat gain of a zone based on the angle of incidence of direct solar radiation on the surface of a glazing.

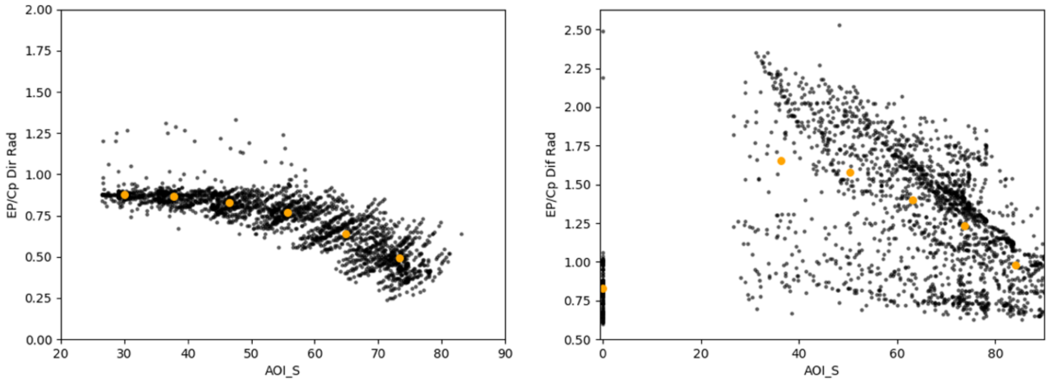


Figure 5.2-2 Angle of incidence dependent coefficients generated using a clustering approach

A direct comparison of solar heat gain for two weeks in winter and summer is shown in the following figure. After using adjustment factors to calculate incident angle solar heat gain coefficients (SHGC), hourly solar gain in *climabox* trails very closes the hourly solar gain in EnergyPlus (RMSE 0.07).

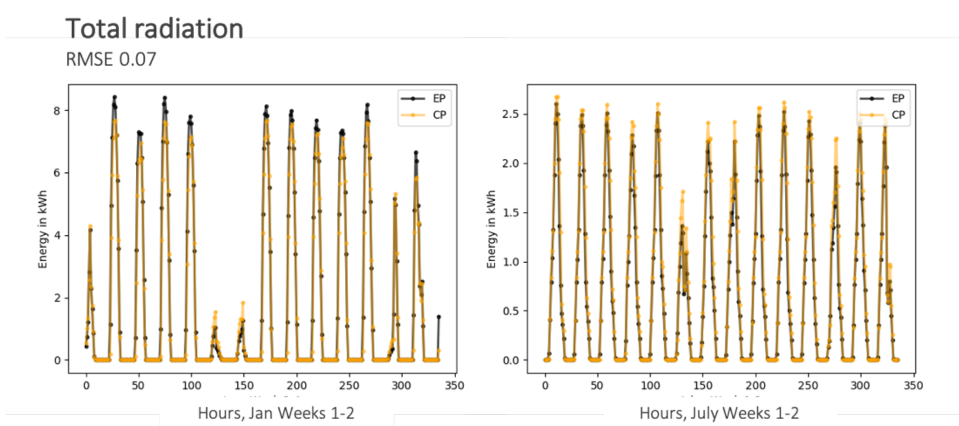


Figure 5.2-3 Direct comparison of hourly total solar heat gain using climabox and EnergyPlus, for two weeks in winter and summer.

Infiltration and ventilation

In the climabox approach, a constant air change rate value is used to represent infiltration rates based on a schedule provided by the user. In comparison, EnergyPlus implements an hourly calculation considering environmental factors such as wind speed and temperature differences in addition to inputs for availability schedules. The hourly comparison of predicted infiltration rates in climabox and EnergyPlus show agreeable results with a RMSE of 0.02.

Due to the complication of determining ventilation air due of uncertainties associated with operation of openings, as well as variable weather conditions that are impacted by context of the building, hourly airflow rates predicted in climabox do not match what is predicted in EnergyPlus. However, the climabox approach is able to predict the times when natural ventilation is available as shown in Figure 5.2-4, even though hourly values differ.

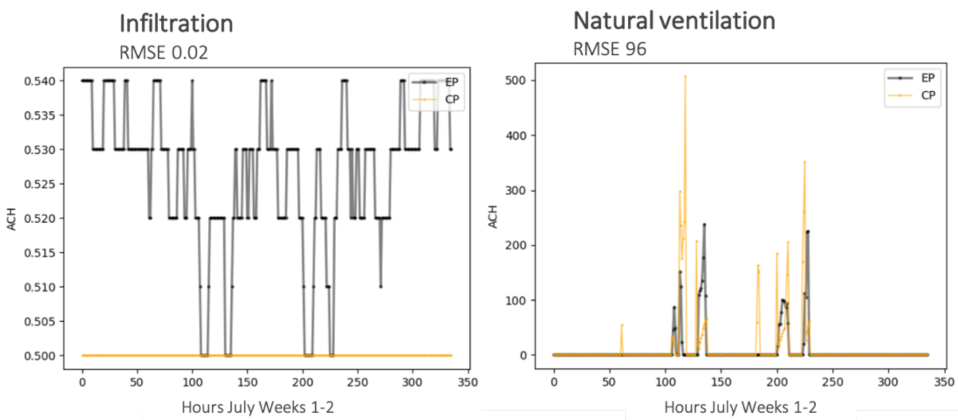


Figure 5.2-4 Direct comparison of hourly infiltration and ventilation airflows using climabox and EnergyPlus, for two weeks in summer.

5.2.2. Model outputs

Predicted hourly indoor temperatures, and heating and cooling loads by the *climabox* approach is compared against EnergyPlus results for similar climate and zone parameters.

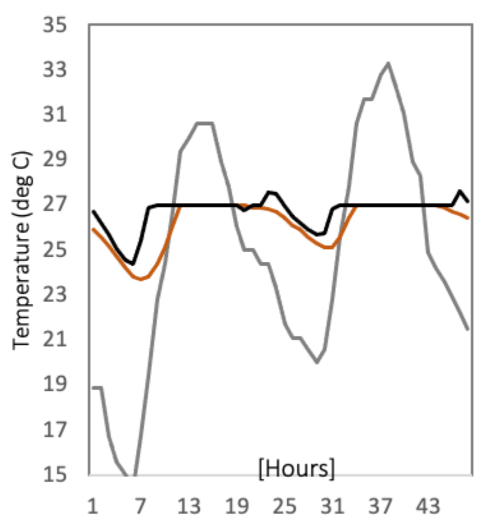


Figure 5.2-5 Predicted hourly in door temperature, two summer days in Denver

Thermal simulation results of the *climabox* approach and EnergyPlus show similar trends for hourly indoor temperatures for fully naturally ventilated or free-floating zones. However, slight differences are observed on heating and cooling loads for conditioned zones.

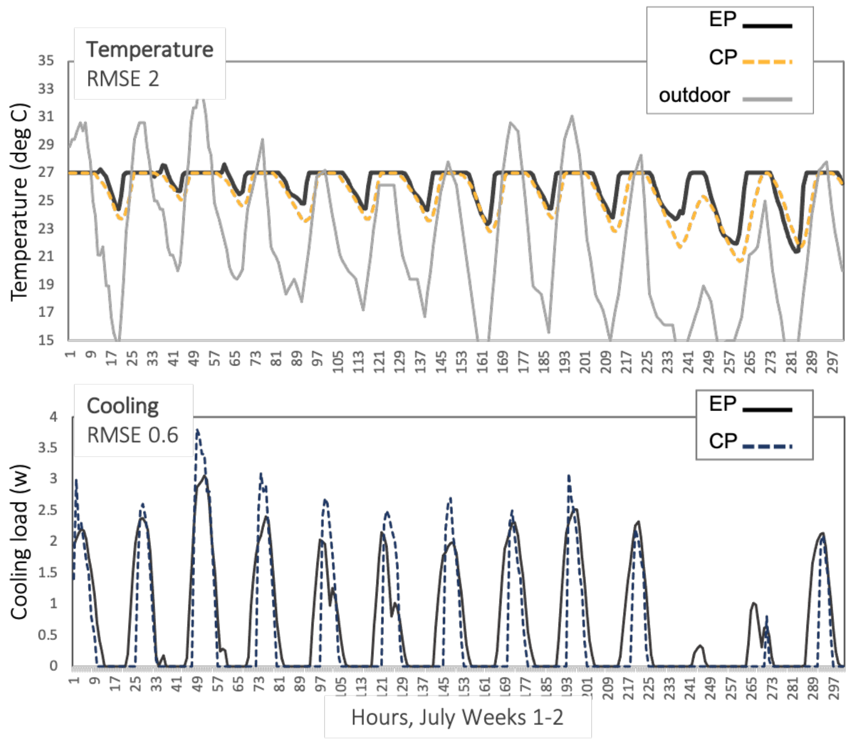


Figure 5.2-6 Direct comparison of hourly temperature and cooling load using climabox and EnergyPlus, for two weeks in summer.

5.3. Pairwise Comparison

A new validation approach using a pairwise comparison of combinations of scenarios is introduced to validate recommendations given by *climabox* against EnergyPlus. Because the goal of the *climabox* approach is not to provide exact predictions of heating and cooling energy loads or numbers of discomfort hours, using only direct comparisons to validate output results has its limitation. The following validation approach is developed to gauge how reliably the *climabox* model guides uses in the right direction when they make decisions on various building strategies.

In the following subsections, the methodology is presented in three parts pertaining to definitions of building scenarios and their pairwise comparisons, validation results matching recommendations given by *climabox* and EnergyPlus, and discussion on the inconsistent cases outlining the limitation of the *climabox* approach and where users should take caution.

5.3.1. Scenarios, combinations, and similarity threshold

For three different cities representing a hot, temperate, and cold climates, various scenarios are defined based on high, medium, and low internal loads, envelope insulation, thermal mass, window-to-wall ratios, and modes of operation as shown below.

CLIMATE	Hot		Phoenix
	Mild		San Francisco
	Cold		Denver
INTERNAL LOAD	LGT	High	10 W/m2
		Low	4 W/m2
	EQPT	High	10 W/m2
		Low	6 W/m2
INSULATION	High		U 0.13 W/K.m2
	Mid		U 1.66 W/K.m2
	Low		U 3.5 W/K.m2
THERMAL MASS	High		
	Mid		
	Low		
NATURAL VENTILATION	On		Temperature Min, out: 18.5 ºC Max, out: 26.5 ºC
	Off		
WWR (SOUTH)	0.3		
	0.6		
	0.9		
CONDITIONING	HEATING	On	Temperature Set point: 18 ºC
		Off	
	COOLING	On	Temperature Set point: 27 ºC
		Off	

Figure 5.3-1 Different building parameters used to generate 2592 different scenarios

The three modes of operation are fully naturally ventilated (324 Scenarios), hybrid (648 scenarios) and conditioned (324 Scenarios) for all three climates. All these pre-defined scenarios are simulated in EnergyPlus as well as the *climabox* model, then using a post-processing script, total energy required for conditioning when heating/cooling is on and total discomfort hours when there is no heating/cooling are calculated for all simulations.

Based on these scenarios, thousands of pairwise combinations are generated parametrically using (algorithm). For example, for one combination of two mechanically conditioned building scenarios is one with a low performance envelope and the other a high-performance envelope, as illustrated in the concept diagram below. For these buildings with installed cooling systems the total cooling energy use intensity is used for comparison, and the scenario with the lowest value is the recommend strategy to reduce cooling.

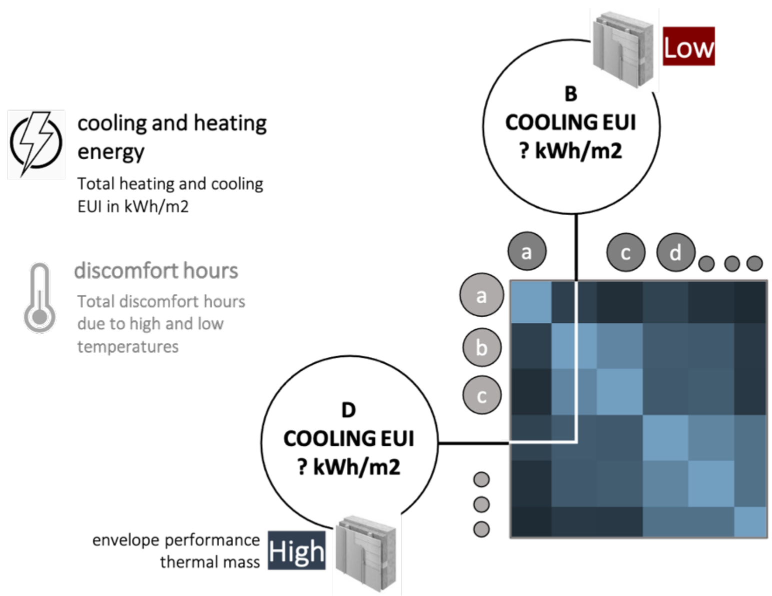


Figure 5.3-2 The concept of the pair wise comparison approach, with an example of a combination of two scenarios

For each pairwise combinations, however, the analysis first checks if the difference between the scenarios is large enough to say one is better than the other. Based on the examples provided in ANSI/ASHRAE 140 guideline for the evaluation of building energy analysis computer programs, a 10% difference threshold (that is, *10% of max [B, D]*) is implemented to identify when two scenarios are not significantly different for both EnergyPlus and *climabox* simulations. In the example presented in *Figure 5.3-2* , the predicted cooling EUI according to the *climabox* approach for scenario *B* is 34 kWh/m^2 while for scenario *D* it is 26 kWh/m^2. The difference between these two scenarios is 8 kWh/m2, which is more than the 10% maximum threshold – the difference is 23.5% of scenario B, which has the largest predicted cooling EUI. Hence, the analysis will mark these to be the same according to climabox. A similar assessment using EnergyPlus predictions shows that the difference between the two scenarios is larger than 10%, hence the analysis continues to the next step. If the comparison using EnergyPlus simulation showed that the two scenarios have a difference of less than 10%, then the result of this specific comparison between *climabox* and EnegyPlus will be *inconsistent*.

The final step is to check if both EnergyPlus and *climabox* have the same ranking – if the answer is yes then we call the comparison matched. The goal of this validation study is to check if the climabox approach ranks pairs of scenarios in a similar manner as EnergyPlus in majority of cases, leading to a conclusion that a user will arrive at a similar recommendation using either of the two simulations methods.

5.3.2. Climabox vs EnergyPlus matching percentages

Results are shown separately for each climate, as pairwise comparisons are generated per climate. Total cooling and heating energy predictions are used for hybrid and fully conditioned cases, while total number of discomfort hours are used for free-floating cases. Here, we report on a total of 23,200 combinations for hybrid and conditioned scenarios, and 5,800 combinations for free-floating.

	HYBRID CB vs EP TOTAL ENERGY MATCHING	H+C (NO NV) CB vs EP TOTAL ENERGY MATCHING	NV CB vs EP TOTAL DISCOMFORT HRS MATCHING
Denver	93.3%	94.6%	92.7%
Phoenix	91.9%	91.5%	92.7%
SF	93.3%	95.3%	95.4%

Figure 5.3-3 EnergyPlus vs climabox, comparison of matching percentages for three climates

5.3.3. Shortcomings of the climabox approach

We have identified primary differences between the simplified RC analytical equation of the *climabox* approach and the EnergyPlus simulation that explain the 10% variation reported in the above pairwise comparison of the two methods.

An approach used to identify when an inconstancy happens between the EnergyPlus and climabox pairwise comparisons is to study different levels of parameter combinations incrementally. This is done by defining scenarios for pair-wise comparisons by changing one, two, three or four of the parameters listed in *Figure 5.3-1* at a time.

Conduction loses and gains

In the analytical model of the climabox, conduction though the building envelope is aggregated to a single heat transfer value, calculated with UA, and the temperature difference (delta T) considered to predict conduction energy is the difference between the outdoor air temperature and indoor air temperature. In comparison, EnergyPlus conduction gains and loses use different outside temperatures for different orientation that is calculated based on the solar radiation on the given surface. This solar-air temperature ($T_{sol\text{-}air}$) in EnergyPlus combines absorbed direct and diffuse solar (short wavelength) radiation heat flux, net long wavelength (thermal) radiation flux exchange with the air and surroundings, and convective flux exchange with outside air, as presented in the Engineering Reference on page 87 (EnergyPlus 2016).

By calculated solar radiation on different surfaces of the *climabox*, a comparison of hourly $T_{sol\text{-}air}$ for South, East, North and West facades with the ambient temperature are shown in the figures below. The following equation, that is also used in (Jakubiec and Reinhart 2013), is used to calculate hourly $T_{sol\text{-}air}$.

$$T_{sol\text{-}air} = T_{amb\text{-}air} + \frac{(\alpha * E)}{hc} \qquad \textit{(Eq 4.2-10)}$$

The air temperature near surfaces tends to be higher than the ambient air temperature because of solar radiation, and the equation above is used to approximate this phenomenon. It is the ambient temperature ($T_{amb\text{-}air}$, C) plus the absorptivity of external surfaces (α, %) multiplied by the incident radiation (E, W/m2) and divided by a convective and radiative loss factor (h_c, $W/m^2.K$). The following figures show hourly $T_{sol\text{-}air}$ and $T_{amb\text{-}air}$ for four different orientations ($\alpha = 0.7,\ hc = 15\frac{W}{m2}K$)

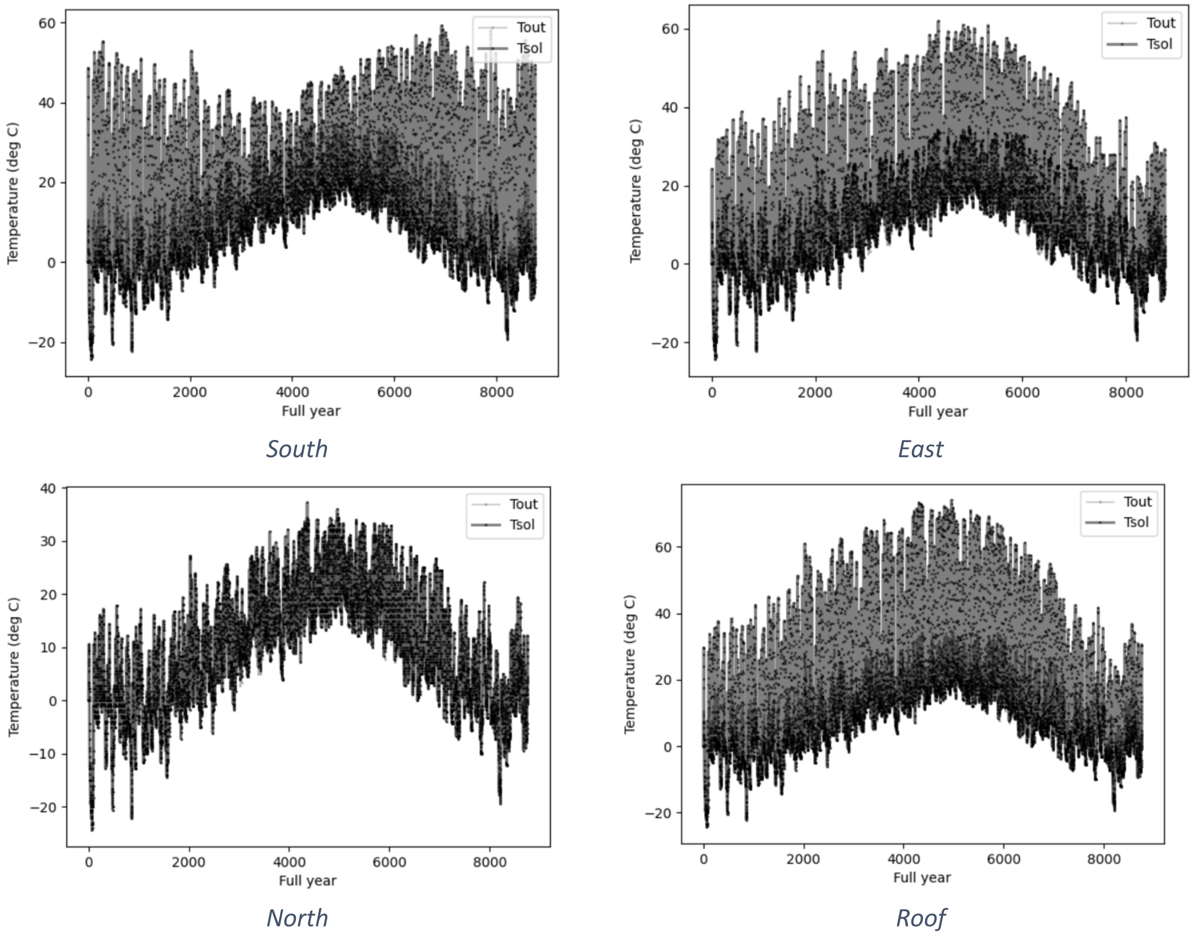


Figure 5.3-4 Solar-air temperature calculated on the south, east, west and north facades, compared with the outdoor ambient temperature

Thermal storage of the envelope

In the simplified RC approach of the *climabox* model, the total thermal storage capacity of the building is represented as an exposed floor area with a given thickness, while the building envelope solemnly has thermal resistance property. Solar radiation and ventilation/infiltration entering the zone though the glazing interact with the thermal mass to affect its temperature, which intern regulate the indoor air temperature. In comparison, envelope construction in the EnergyPlus model uses a construction module defined by layers of construction materials, including insulation and cladding, representing the specified thermal resistance values. It is important to note that the different envelope performances (high, medium, and low conductions) are achieved by adjusting the thickness of the insulation layer, which also has some thermal capacitance that is small compared to high thermal mass materials such as concrete. In the validation study different dampening effects in the indoor air temperature as the insulation levels increased from low to medium to high performance were observed in the comparison of scenarios with similar exposed floor thermal mass area.

5.4. Improving the *climabox* approach

To address the limitations of the analytical model that caused the inconsistencies observed in the pair-wise validation study, we explored alternative ways to adjust the RC analytical model.

Including solar-air temperature ($T_{sol-air}$)

To account for the heat balance at the outer surface of zone using a Tsol-air, that would be used in lieu to the ambient temperature (Tout) to calculate conduction losses and gains. The following diagram is a modification of the RC model presented (section . . . RC Model) with Tsol-air.

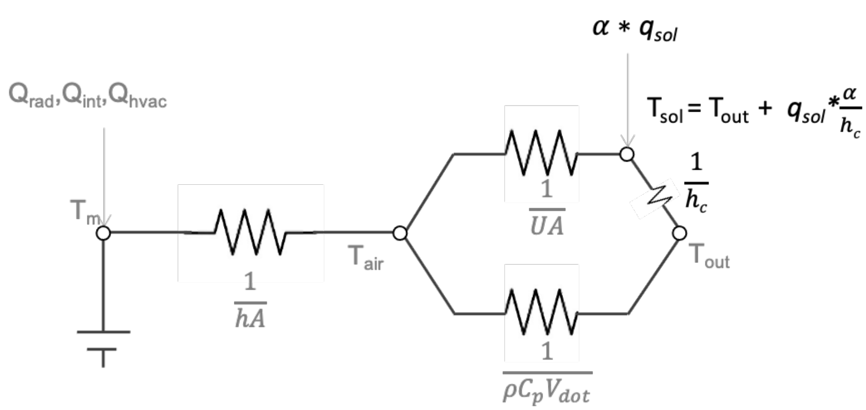


Figure 5.4-1 The RC model diagram used in climabox, with Tsol-air.

However, incorporating solar-air temperature in *climabox*'s RC model which has a single capacitance model is challenging where the wall thermal capacitance is not considered separately. To see what an alternative model can be implemented, we further adjusted the diagram above to an 4R2C model, that has two thermal capacitances at the internal thermal mass and building envelope.

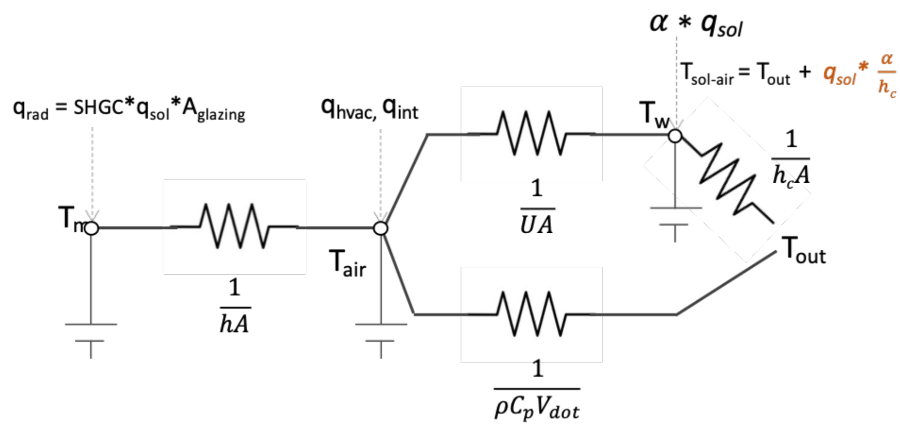


Figure 5.4-2 Suggested modification to the original RC model diagram used in climabox with $T_{sol\text{-}air}$

The following differential equations (*Equs 5.4-3 to 5.4-6*) are defined for three nodes at the center of the internal thermal mass (T_m), indoor zone air (T_{air}), and external wall or building envelope (T_w).

$$C_m \frac{dTm}{dt} = \frac{Ta - Tm}{Rma} + q_{rad}$$

$$C_a \frac{dTa}{dt} = \frac{Tm - Ta}{Rma} + \frac{Tw - Ta}{Rwi} + q_{hvac} + q_{inf}$$

$$C_a \frac{dTa}{dt} = \frac{Tm - Ta}{Rma} + \frac{Tw - Ta}{Rwi} + q_{hvac} + q_{inf}, \text{where } C_a = 0$$

$$C_w \frac{dTw}{dt} = \frac{Ta - Tw}{Rwi} + \frac{To - Tw}{Rwo} + \alpha * q_{sol}$$

Future work will include a validation comparison of the RC model with the 4R2C model and will identify which analytical approach provides results that better match EnergyPlus simulations.

5.5. Conclusion

The validation is done for model inputs as well as model outputs using the commonly used direct comparison approach based on ASHRAE 140, as well as a pairwise comparison, a new approach specifically designed for this validation analysis.

The following conclusions are made regarding input parameters of the *climabox* approach. It has similar hourly loads from lighting, equipment, and occupants (RMSE 0.02) by using similar schedules used in EnergyPlus. The solar heat gain calculated using a simple glazing in *climabox* is adjusted using incident angle dependent coefficients. These coefficients are applicable for openings in different orientations. Infiltration and ventilation due to wind and buoyancy can be controlled using indoor setpoint temperatures and outdoor minimum and maximum temperatures.

The validation study has shown that the climabox approach can guide users in the right direction of when making decision of building strategies. However, the approach is not meant to predict exact energy use values or comfort hours for a single scenario. Furthermore, the proposed pairwise comparison validation methodology can be used for validation studies of early design stage tools.

Chapter 6 - High impact teaching

In this portion of the work, I describe content delivery and lessons learnt from teaching a MOOC on sustainable building design for over 40,000 learners world-wide via the EdX platforms from MIT. The class was administered three times since January, 2020 and is an online version of a required introductory class on bioclimatic design, daylighting and energy for graduate and undergraduate students in architecture at MIT (Reinhart et al. 2015). The course is also an elective for MIT's Energy Minor for undergraduate students and thus attracts a variety of additional students from across the institute. The online version was developed in collaboration with MITEI and will form part of a MicroMaster in Energy with other three courses being offered from the business school, engineering school and MITEI.

By assessing how online learners have been engaging with the MOOC course and by using thousands of survey responses provided by learners before, during and after taking the course, the study explores the following research questions:

> Given the large enrollment of learners for the course, **who completes** and who doesn't complete the course successfully?
>
> How can the course be improved to support **struggling learners** who couldn't get a passing grade despite their active participation in the course?
>
> Is **peer assessment** reliable to provide equitable and fair assessment of learners' projects?

The aim is to have a better understanding of learners' behaviors, which would be used to develop and implement teaching strategies and course interventions that improve learners' success. This chapter presents the challenges and lessons learned from teaching a university level course on sustainable building design to thousands of learners worldwide.

6.1. Goals for the MOOC

It is established that the building sector is a contributor to approximately 40% of global carbon emissions, but offers opportunity for substantial, economical energy efficiency gains. A series of technologies, such as rooftop solar systems, better window glazing systems, insulation upgrades, and other passive building design strategies are enabling buildings to generate as much energy on-site as is utilized over a year ("net-zero energy"). To make net-zero energy building design attainable worldwide, a context-specific design process should apply technologies and strategies to retrofit and new building projects, finding optimal solutions that meet local climate needs, cultural expectations, and financial constraints.

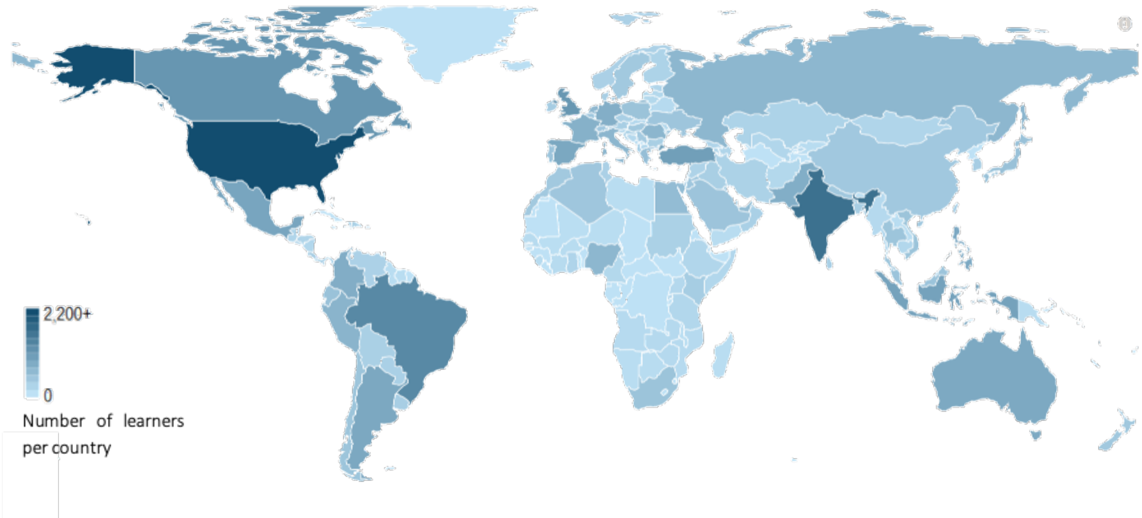


Figure 6.1-1 Geographic distribution of MOOC learners worldwide

To build a global cadre of architects, builders, and planners driving these principles of climate-responsive, sustainable building design, Professor Christoph Reinhart (MIT School of Architecture and Planning, MIT Sustainable Design Lab) collaborated with the MIT Energy Initiative (MITEI) to create “Sustainable Building Design”, a massive open online course (MOOC) for the popular online learning platform edX. The MOOC has since attracted over 40,000 enrollees, and became the first in the series of four graduate-level, energy-related courses developed by MITEI to impart specific skills necessary for expediting the worldwide transition to clean energy infrastructure.

From the onset, the MOOC team was intent on translating the active, hands-on learning approach on MIT’s campus to the online space. The residential course “Environmental Technologies in Buildings”, the popular, interdisciplinary course upon which the MOOC was based, was taught at MIT since 2012. The course guides MIT students through the study of bioclimatic design, daylighting and energy use of buildings, and hands-on experience with a range of technologies and analysis techniques used to create comfortable, efficient indoor environments.

6.2. Delivery method and challenges

The process of translating an in-person course online is seldom linear, and a course centered on design principles presents a particular set of opportunities and challenges for the MOOC format. In this next section, the strategies and decisions made in designing this particular MOOC will be described.

*Lectures, intercepted with comprehension questions to promote **active learning***

One of the more straightforward but time-consuming tasks involved preparing lecture videos. The series of 18 filmed lectures and slides, captured during his 2018 fall offering of the course at MIT, provide the backbone of the MOOC. These lectures, each approximately 90 minutes, are sectioned into smaller, 10 - 20-minute topical units in order to better suit the attention span of online learners. The instructor reviewed footage of all his videos, identifying natural breaking points within the larger lecture and removing off-topic or outdated comments from himself and students. The lectures were then organized into three larger modules: Benchmarking and climate, Daylighting, and Thermal Loads. Once final edits were made to each unit, mp4 files were uploaded to a third party to generate timed transcripts in accordance with edX's accessibility standards. Although the transcripts were relatively accurate, each needed to be reviewed and edited for accuracy.

To promote active learning, lecture units were interspersed with low-stakes quiz (or "comprehension") questions designed to prompt learners to further engage course concepts, gauge their understanding of them, and increase retention. Comprehension questions range in difficulty, and typically take the form of multiple choice, checkbox, or text/numeric input. Discussion boards, moderated by course staff, allow learners to raise questions and offer their own observations and experience.

*Weekly assignments to build **analysis skills***

At the end of a series of lectures and comprehension questions, participants have to work through a weekly assignment. These in-depth exercises were designed to help learners explore and develop a specific applicable skill, and also emphasized skills learners would need to complete a final design project. These assignments at the end of each week distinguish the MOOC as graduate-level. Each assignment prompts learners to explore innovative analysis tools and techniques, and apply them to realistic design scenarios. After completing these 10 assignments, learners draw from those tools and techniques to develop a sustainable building proposal at a location of their choice.

***Equitable access**: 2-track approach to assignments and final project*

A key goal of the MOOC was to ensure that learners from all socio-economic backgrounds could access and understand the content. Given the variety of participant background a 2-track learning model was developed. Whereas students of the in-residence class have access to professional design software and computers, online learners may have anything from simple smart phones or shared community computers to professional-grade systems. Learners could complete assignments either via Track 1, using professional software and equipment, or Track 2, utilizing a suite of freely accessible, browser-based tools selected and tested by the MOOC team.

The first track largely mirrors the in-residence version of the class and is based on state-of-the-art software such as Rhinoceros 3D (McNeel 2021) and ClimateStudio (Solemma 2021) for geometry modeling and environmental performance analysis.

The second track is based on a minimum technology approach requiring participants to have access to a smart phone or other internet connected device with a web browser. As an example, for several assignments learners could use ClimaPlus, a climate-responsive design platform that is entirely free and browser based. It utilizes weather data files from around the world to build local climate profiles and allows users to model how various design decisions affect a building's finances, energy use, and greenhouse gas emissions. Using either simplified or state of the art design tools, all learners can thus explore the complex interactions between building design decisions, operational energy costs and the impact of a building on climate change.

Scaling design assignments for thousands of learners

Another challenge involved scaling gradable assignments for a large, unpredictable number of learners. Some course content, more quantitative in nature, was well suited to automated machine grading on the platform, with learners answering calculation-based questions via multiple choice, numeric input, etc. Design tasks, however, do not produce uniform responses that can be easily machine graded and the MOOC team essentially built new assignments within those constraints while maintaining key learning objectives.

Week 2's direct shading assignment illustrates several of the MOOC team's responses to such challenges. The goal of the exercise is for learners to verify the accuracy of digital modeling software that replicates natural light behavior in design models, and thereby allows designers to increase the use of natural daylighting versus electrical lighting. To do this, the learners compare real-life effects and digital modeling by photographing an object at 2 times of the day, and then creating a digital model of the object and inputting the time/date and orientation to compare the shading effect. The figure below shows a shading study comparing a photographed object with its exact reproduction in Rhinoceros 3D and ClimateStudio.

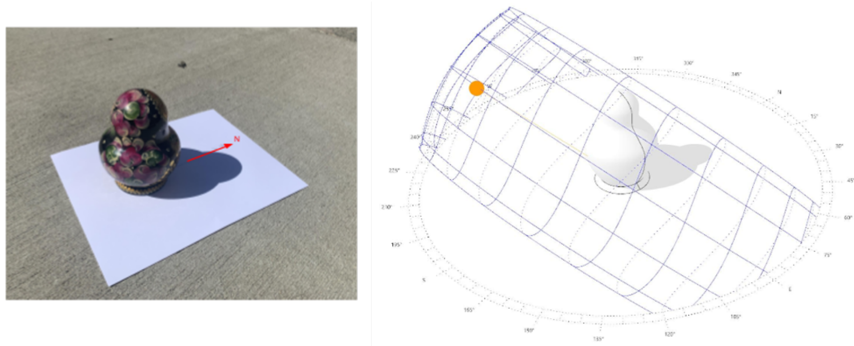


Figure 6.2-1 An example of a learner's shading study

When conducted on campus, executing this exercise is quite straightforward, as students are instructed to use ClimateStudio to create a digital model and replicate the shading effect they photographed. However, it needed careful retooling for the online platform. First, what if the weather is too rainy or overcast and online learners cannot photograph an object casting shade? To avoid a spate of extension requests and general course derailment, the course team uploaded "stock" resources: pictures of stacks of blocks set up and casting shade, taken at two different points in the day, with object dimensions and location information included. These resources could be utilized in the event of inclement weather in the learners' locales. Then, for learners without access to modeling software, the course team identified two free online, browser-based resources. The first, 3D Slash ("3D Slash" 2021), allows learners to quickly and easily create detailed digital models which can be exported as object (.obj) files. Then, in 3D Sun-path (Marsh 2021), allows users to import an object file and input locational and date information to realistically render sun shading effects. Thus, learners may freely model the object they photographed and compare the results.

The final hurdle involved assessment. As a teaching assistant could not possibly review thousands of submissions of photographs and digital models, the MOOC team used the edX platform's open-response assessment function. This allows learners to submit projects in PDF, Word, JPEG, or open text formats. Their submissions are assigned within the pool of other submitters for a peer review, and they are automatically assigned a set number to review. The final grade is the median score across those peer reviews. The rubric was carefully designed to be intuitive and straightforward so that peers did not need to be experts in the software or analysis to verify each other's submissions. Instead, they evaluated 3 key components: whether the required photographs and models were submitted, the degree to which the digital models resembled the photographed objects, and a small discretionary percentage for the complexity of the object modeled. Peers were instructed to focus on the care put into the project, not the aesthetic appeal alone, to mitigate bias toward glossier, "professional models". Peers were also given the option to leave feedback on how they believe the peer-review process went after reading their reviews. The course staff would review the feedback and regrade any projects that needed an extra set of eyes based on peers feedback. The benefit of this open response peer review system is not only a scalable grading mechanism, but a chance for learners to critically evaluate others' approaches to the assignment prompt, reflect on their own, and receive feedback from their peers. Through this process, key learning objectives can be effectively reinforced.

6.3. Who completes the course?

The MOOC course is accessible at no cost to anyone in any part of the world (audit learners). An alternative course registration is available for learners who are seeking certificates (verified learners) for $99. It has been administered three times until Sept 2021, each run lasted from 12 to 14 weeks: the first MOOC run from Jan 15 – April 28, 2020, the second MOOC from Jun 23 – Sept 22, 2020, and the third run from May 25 – Aug 24, 2021. The analysis presented here is based on anonymized and aggregated data from pre- and post-surveys, as well as learners' performance data form the edX platform.

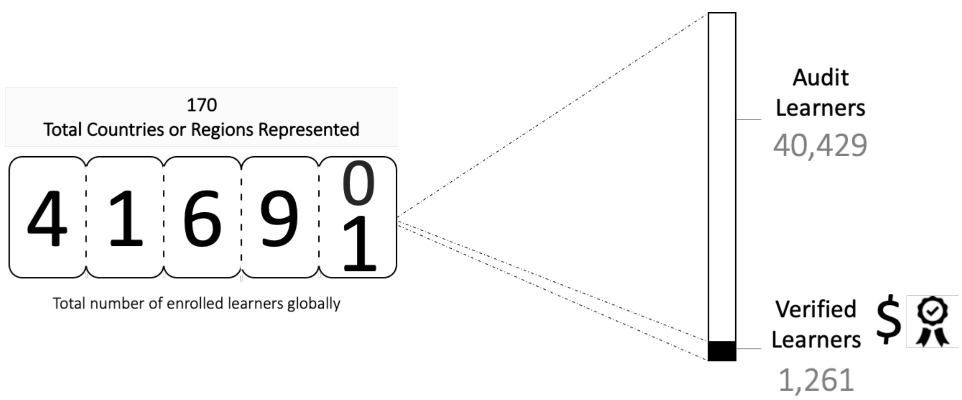


Figure 6.3-1 Audit and verified learners

The 2020-21 lockdown due to the pandemic started while the first run was being administered. Even though the MOOC is an online course and the delivery of the course was not directly interrupted, some learners from different parts of the world have described that the pandemic has impacted their engagement and performance.

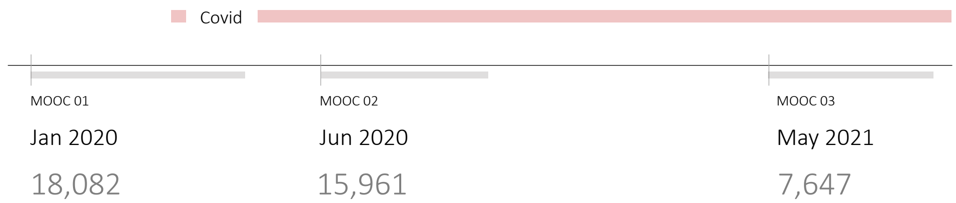


Figure 6.3-2 Timeline of MOOC runs administered from Jan 2020 to Sept 2021

The three MOOC runs were administered similarly in general, with the following few differences. To provide respite for the time learners lost due to personal health, familial responsibilities, or stress due to work conditions, the course team extended the submission deadline for the final project by two weeks in the first MOOC. For the following MOOCs, the team made adjustments in assignment deadlines. Instead of requiring learner to submit assignments every week, they are allowed to submit assignments within a module any time before the module ends.

For the first MOOC, the passing grade was 60%, and while in the second and third MOOCs, it was adjusted to 70% in response to changing online teaching protocols at edX. The final project carried 30% of the overall grade in the first MOOC and it was evaluated by experts. In the second and third runs, peer evaluations of the final project were introduced, and the final project carried 20% of the overall grade. Submission of the final project is not mandatory to pass the course, allowing learners who performed well in the assignments to get the minimum passing score. These variations in the delivery of the three runs are considered in the following analyses.

To better understand learners' experience and the challenges that impacted their performance, the team gathered post-survey responses by the end of each MOOC run. This section will highlight some of findings regarding what impacted learners' success in the course.

6.3.1. The "funnel" effect

Having a large enrollment – 41,690 individuals from 178 countries – could be a good indicator of a general interest on the MOOC and the topic of sustainable building design. However, data on learners' participation shows that only **1.6%** completed the course with a passing grade. From the total enrolment across the three runs, 97% of learners are *audit* learners, with a much lower completion percentage of **0.1%**. On other hand, *verified* learners, although accounting for only 3% of total enrollment, the percentage of course completion is **53%**.

Among the 683 learners who successfully completed the course across the three runs, 95.5% are verified learners who earned a certificate. The second MOOC where we had the largest number of verified learners had the largest dropout, only 41% completing the course with a passing grade among 783 learners. In comparison, about 72% and 68% of verified learners completed the course in the first and third MOOCs from 222 and 256 verified learners, respectively.

When do most learners drop out or stop course participation?

Identifying when during the course most learners stop engaging could indicate if the course structure itself caused decreased activity and when certain interventions by the course team could be used as a tool to boost learner's participation. The course platform allows learners to 'un-enroll' with a simple button, although most learners just stop engaging with the course without canceling their enrollment – from 573 verified learners who haven't completed the course, only 34 unenrolled themselves. As shown in the figure below, dates when these leaners had their last activity in the course are dispersed throughout the course runs. This shows that even learners who are not actively engaging in the course, visit the course platform throughout the course.

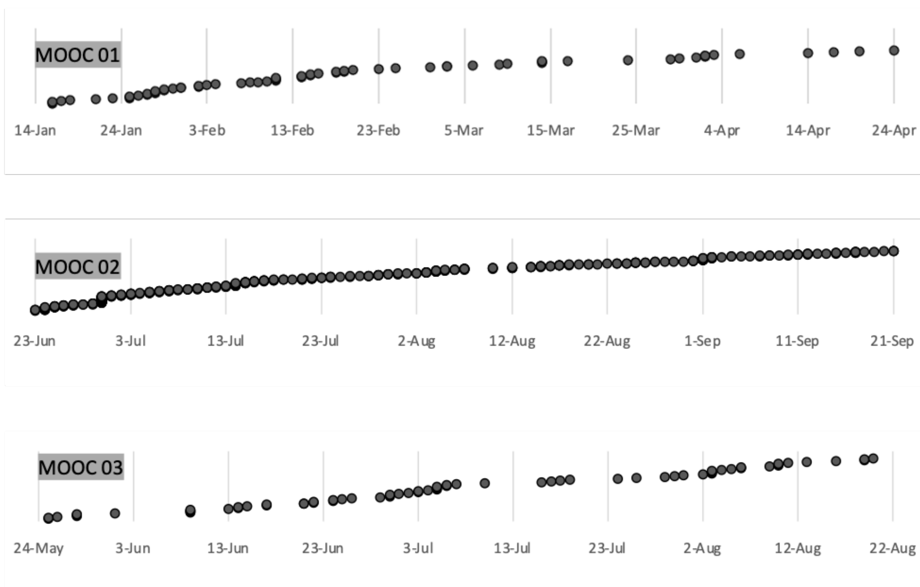


Figure 6.3-3 Dates when learners who haven't completed the course had their last activity in the course

Results on the demographics of learners who successfully completed the course are shown below to identify how gender, education, age, or country/geographic region correlates with learners' successful completion of the course. From a total of 41,690 learners, about 63% of learners had participated in the pre-course survey about their age, educational background, country, and additional questions regarding their plans in participating in the course. A separate post-course survey was conducted, primarily targeting learners who worked on a final course project, with a total of 300 responses

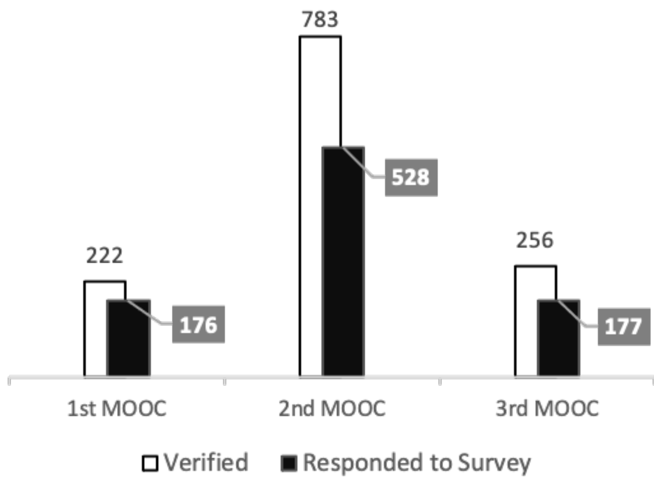


Figure 6.3-4 MOOC learners who responded to items in the pre-course survey about their age, educational background and country

Gender

As shown in *Figure 6.3-5* female learners are generally smaller in number compared to male learners. And this gender distribution is found to be consistent among all learner, verified learners and those who completed the course.

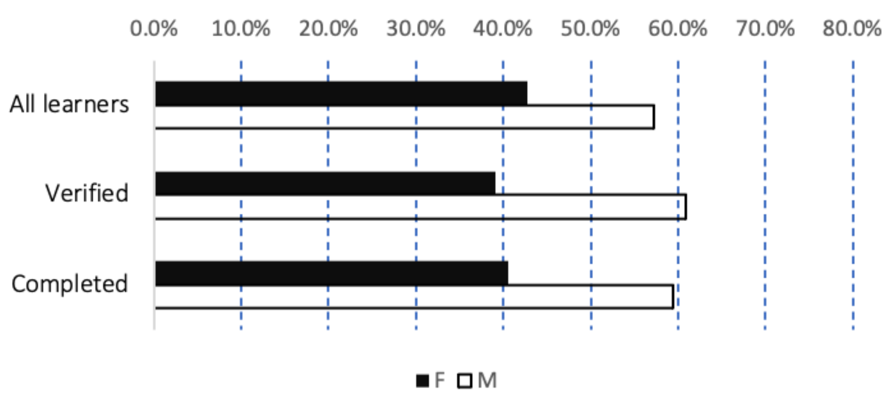


Figure 6.3-5 Gender distribution for all MOOC runs, for all learners, verified learners and those who completed the course.

However, when we look at the percentages of female learners for the 1st, 2nd and 3rd MOOC runs, some variations are observed. The 1st MOOC has the biggest difference between male and female learners who completed the course, while the 3rd MOOC has the smallest difference as shown in *Figure 6.3-6.*

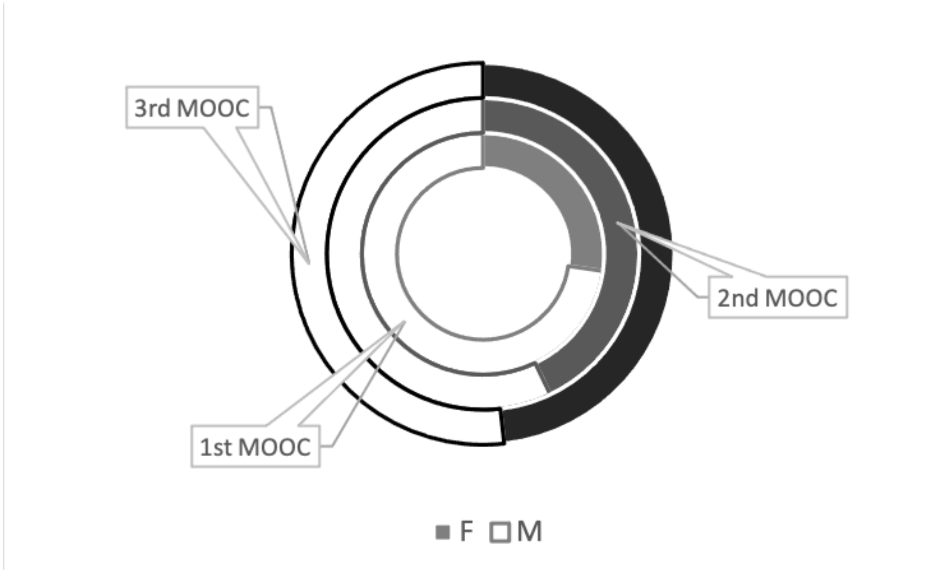


Figure 6.3-6 Male and female learners who completed the course in the 1st, 2nd and 3rd MOOC runs.

When just looking at the percentage of female learners in the first MOOC run, female learners represented about 40% of all learners, while only representing about 27% of those who completed the course.

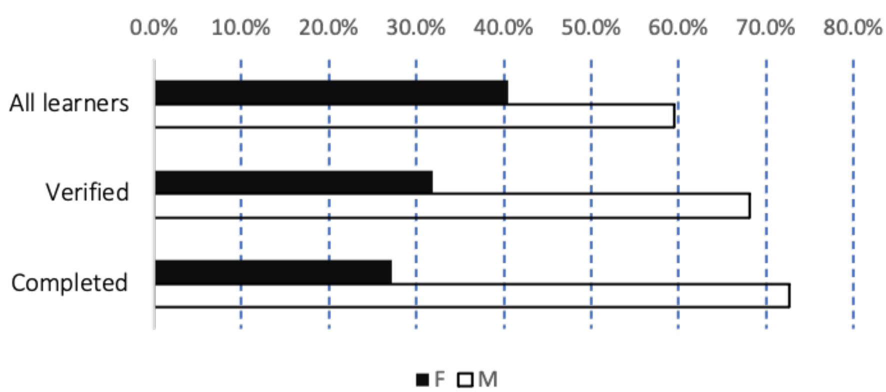


*Figure 6.3-7 Gender distribution for the **first** MOOC run, for all learners, verified learners and those who completed the course.*

Age

Learners are categorized into three age groups for this analysis: 25 and under, between 26 and 40, and 41 and over.

As shown in the figure below, learners who are between ages 26 and 40 are generally larger in number compared to the other age groups among all learners, including both audit and verified learners. However, this age distribution is found to be inconsistent among verified learner and those who completed the course with the majority being learners who are 25 and under.

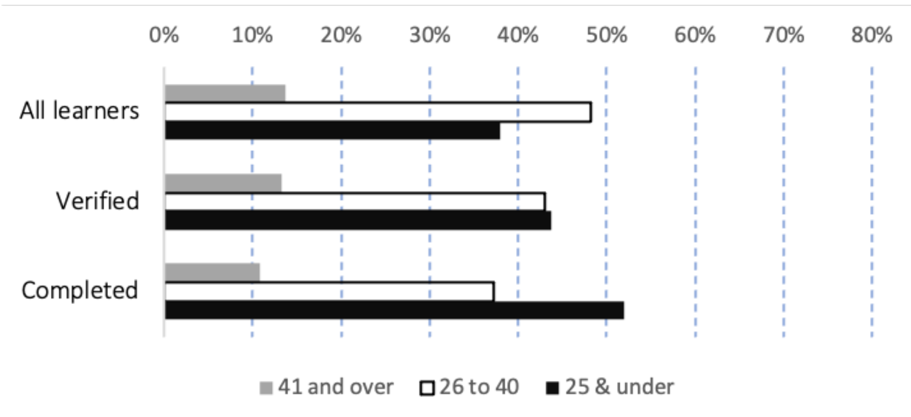


Figure 6.3-8 Age distribution for all MOOC runs, for all learners, verified learners and those who completed the course.

Additionally, when we look at the percentages of different age group learners for the 1st, 2nd and 3rd MOOC runs separately, some variations are observed. In the second MOOC, even though learners who are 25 or under represent 43% of all learners, they make up 74% of all learners who completed the course. Learners who are between 26 and 40 years of age, in contrast, significantly drop from 45% (of all learners) to 15% (of those who completed the course). In agreement with the overall trend shown in Figure 6.3-9, the 1st and 3rd MOOC learners who are between 26 and 40 year of age represent the largest proportion of learners among verified learners as well as those who completed the course. For example, in the 1st MOOC 68% of learners who completed the course are of age 26-40 while 17% are those 25 and under.

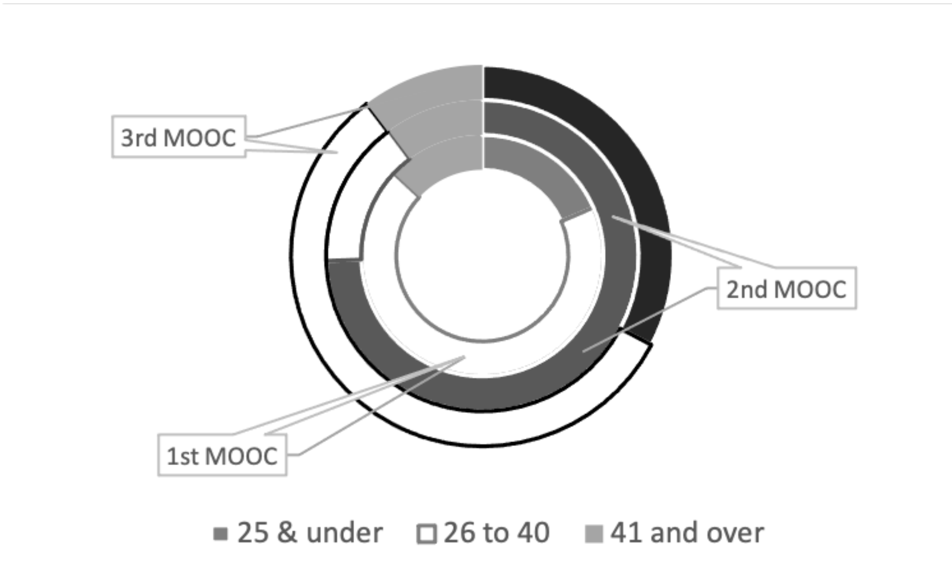


Figure 6.3-9 Learners of different age groups who completed the course in the 1st, 2nd and 3rd MOOC runs.

We took a closer look at the profile of learners who are under 25 in the 2nd MOOC to understand their educational background, specifically the highest level achieved. Fostering a high engagement among the youngest participants is key to high impact online education, as the young generation will form the future professionals who would make design and policy decisions in the building industry. The figure below shows that majority of the learners who completed the course in the 2nd MOOC, who are 25 and under, have a bachelor's degree (about 45%) and learners with high school diploma are the second largest (about 23%). This analysis shows that learners with some college degree tend to succeed in the course, and this is not surprising given the course is an online version of a university level course.

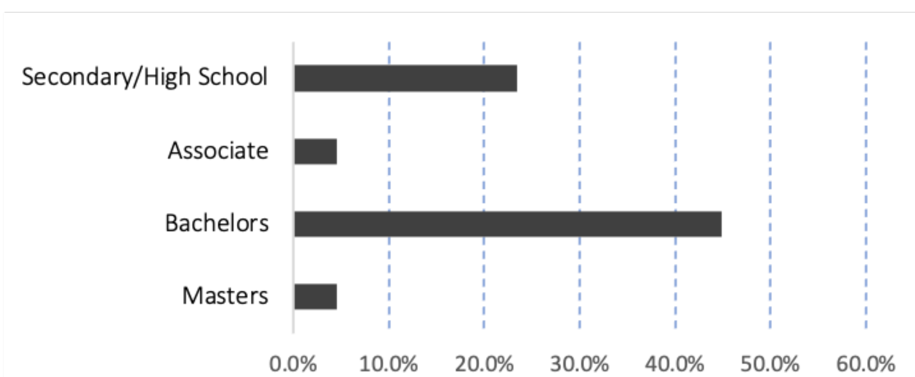


Figure 6.3-10 Education background of learners 25 years of age and under, who completed the course in the 2nd MOOC run

Geographic distribution

Here we summarize participation levels of learners across different continents. We are particularly interested to evaluate where the MOOC course has large as well as low participation. In regions in the developing world with low course enrollment, we would like to address challenges that reduced accessibility of the course.

Figure 6.3-11 The UN regional groupings, used to assess millennium development goals. From mdgs.un.org

(http://news.bbc.co.uk/nol/shared/bsp/hi/dhtml_slides/10/millennium_goals/inc/slideshow.inc)

From the total enrollment in all three MOOC runs, the largest number of learners, including both verified and audit, are from Asia -- 33%, verified learners (45%) and learners who completed the course (36%). Oceania was represented with only 2% enrollment. Followed by Africa and South America that have low enrollments -- 7% of learners and 13% who registered for the course, respectively. The second and third run have similar distribution pattern as the overall figure shown below.

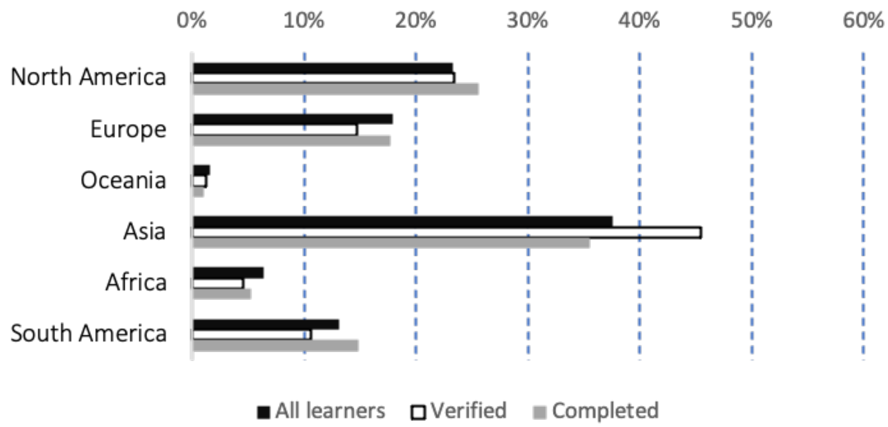


Figure 6.3-12 Geographic distribution of MOOC learners from all runs in percentages across continents

The first MOOC run, however, has a slightly different distribution. The largest number of learners, including both verified and audit, are from Asia -- 33%, but the majority of verified learners are from North America (41%) and Europe (26%). These learners also represent 55% of learners who completed the course as shown in *Figure 6.3-13*. This shows that there is increased participation in Asian countries in the second and third runs, while learners from North America and Europe decreased slightly. There weren't large variations in the number of learners from Africa and South America across the three runs, and percentages remained between 5% - 15% of total enrollments.

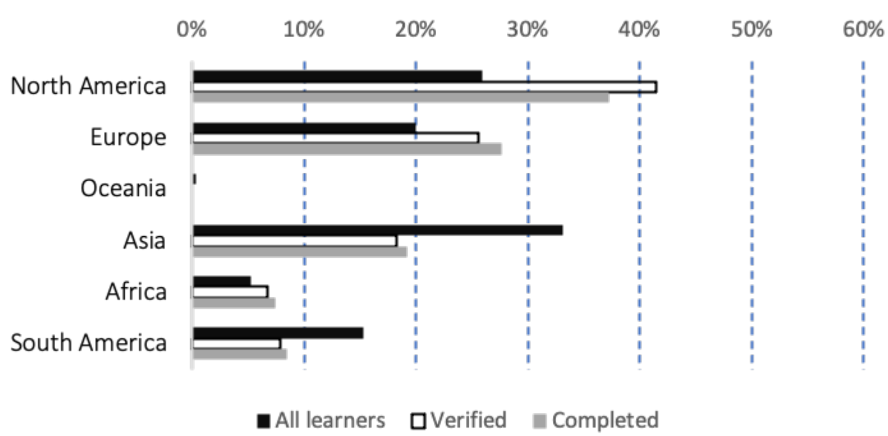


Figure 6.3-13 Geographic distribution of MOOC learners from the first run, in percentages across continents

The lowest completion rate is observed among Asian learners, who represent the largest number of verified learners, 600, among all learners. On the other hand, South America has the highest rate of completion of 64%, however number of verified learners from South America is one of the lowest with a total of 128 learners. Completion rate among learners from North America, Europe and Africa is 50 -55%.

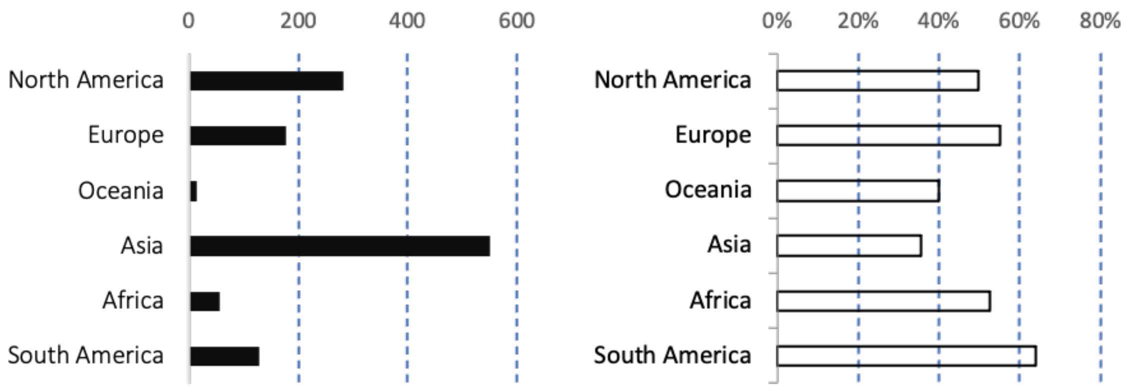


Figure 6.3-14 Total number of verified learners (left) and percentage of verified learners who completed the course

The four developing countries with the largest number of registered verified learners are India, Brazil, Turkey and Mexico (Figure 6.3-15). Among the 5000 learners from these four countries, only 0.5% completed the course with a passing grade, which is a much smaller percentage compared to the overall 53% completion percentage of verified learners. By making web-based approach available in the second track, the goal is by allowing the course to be completed from any internet connected device, to make the course accessible to learners who do not have access to powerful computers. Based on learners response in the post survey, lack of access to internet was not one of the primary limiting factors affecting completion of the course.

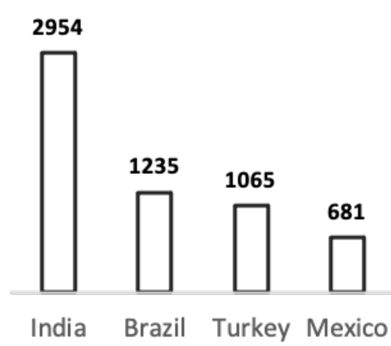


Figure 6.3-15 The top four developing countries with the largest enrollments

Education

Across the three runs, majority of learners who enrolled as audit or verified, as well as those who completed the course have some college degree. This finding aligns with learners' response on post-surveys where 70% described professional growth and career goals as a primary motivation for taking the course.

Learners with high school diploma or less make up less than 12% of learners who competed the course, even though they represent 30% of all learners and 28% of verified learners. *Figure 4.3-16* shows that even though there was large interest among learners with high school diploma or less, their number drops by more than half at the end of the course.

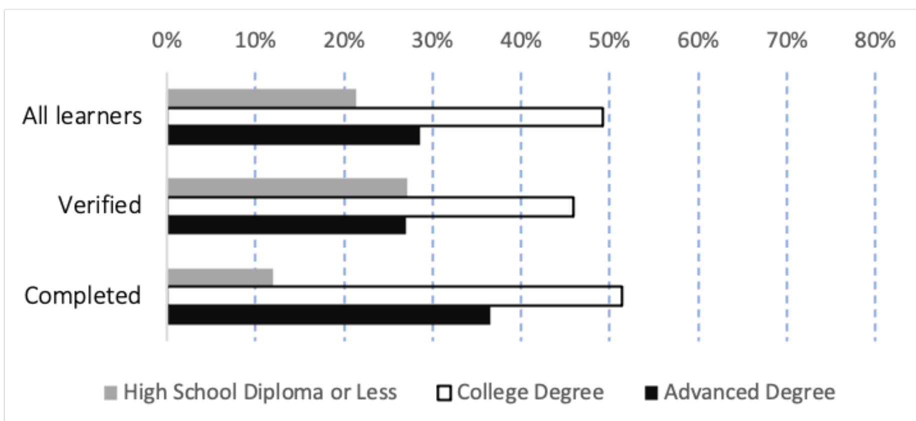


Figure 6.3-16 Academic background of all MOOC runs, for all learners, verified learners and those who completed the course.

Similar pattern is observed across the three MOOC runs, where about three-fourth of registered learners already have university level education, while about 15% have high school diploma. The following figure shows the breakdown of academic background of learners in the second MOOC run. More than 50% of learners who completed the course have bachelor's degree, and about 30% have master's degree.

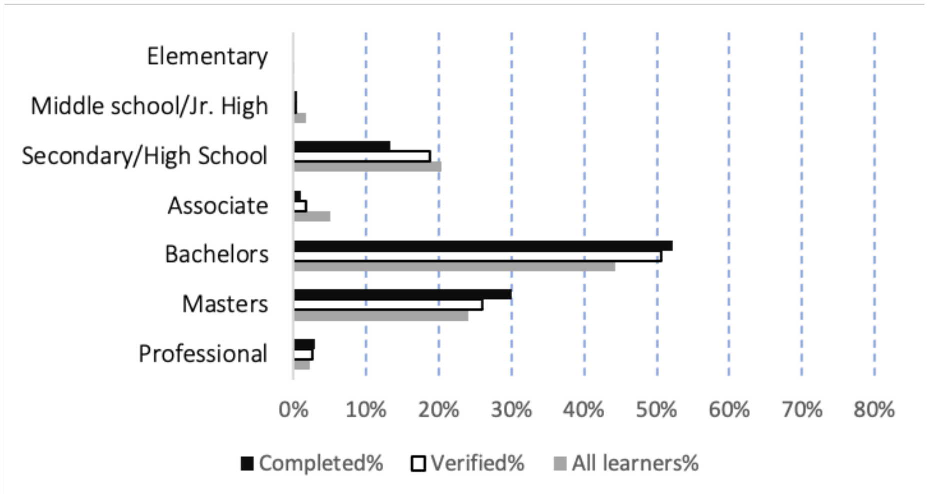


Figure 6.3-17 Academic background of 2nd MOOC all learners, verified learners and those who completed the course.

Background in Architecture and related fields

Among the total number of verified learners across the three runs 1261 (53% have completed the course with a passing grade), 338 have shared their feedback on a post-survey that was made available after learners have submitted their final project. About 90% of these learners are working or have training in architecture, engineering, or construction, while 8% of learners are studying or working in a different field.

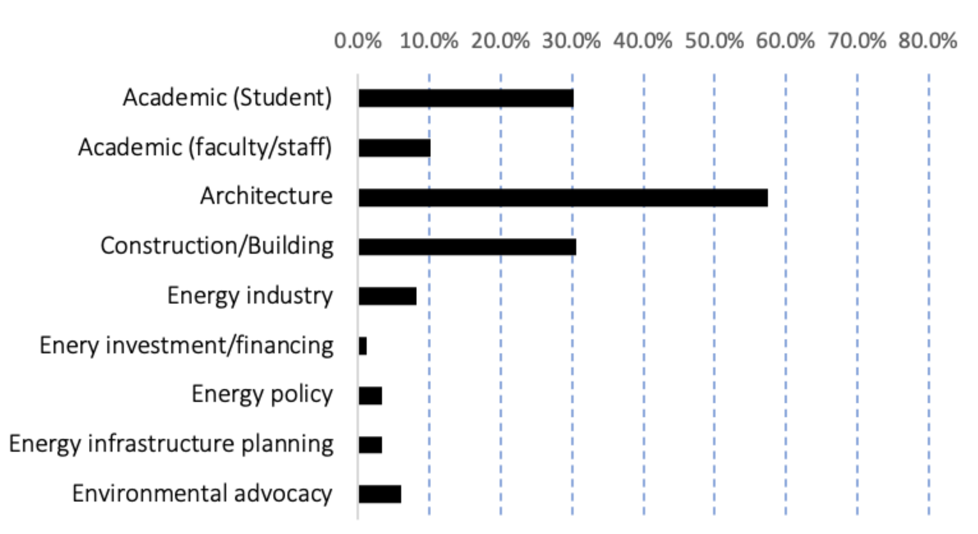
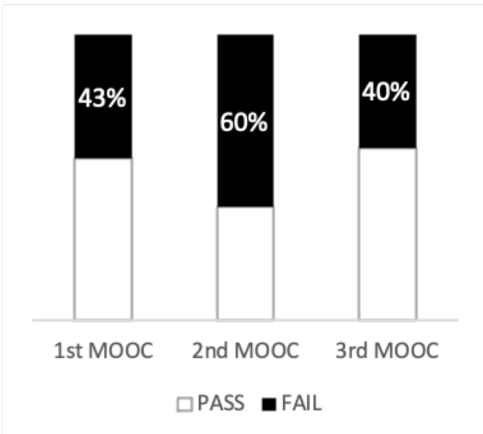


Figure 6.3-18 Sectors learners are working or have training in, based on a post-survey.

6.3.2. Who doesn't complete the course?

Learners who couldn't complete the course participated in the course in varying capacities: some learners had no engagement at all, without even once accessing the course, while some others stayed on the course until the end, watching few lecture videos and submitting a couple of assignments. To quantify how much these learners participated in the course, we are showing selected participation parameters. The figure below shows 13% of learners from the three runs who didn't complete the course watched more than 50% of lecture videos while about 17% of these learners had their last activity on the platform in the second half of the course.



	1st MOOC	*2nd MOOC*	*3rd MOOC*
Haven't viewed the class	*13%*	*18%*	*5%*
Watched > 50% videos	*12%*	*10%*	*24%*
Last activity after mid-course	*39%*	*7%*	*40%*

Figure 6.3-19 Percentages and activities of verified learners that haven't completed the course

Activity profiles of learners who haven't completed the course are shown in terms of total number of learners' activities in the course platform, including participation on discussion boards, attempted quizzes, assignment submissions, and watched lecture videos. In comparison to learners who completed the course, learners who haven't completed the course do only half the number of activities. The figure below shows that the median number of activities for all the three runs ranged between 200 and 600 events for learners who haven't completed the course, while for those who completed the course the median number of activities ranged between 1500-2000.

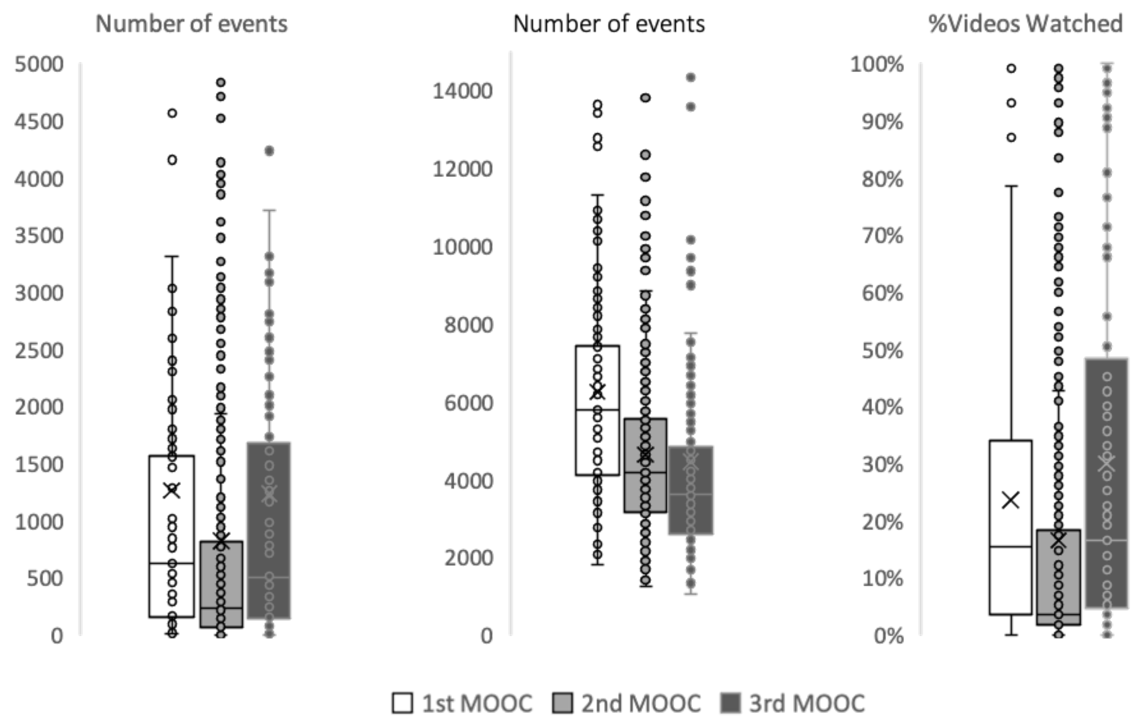


Figure 6.3-20 Activities of verified learners who have not completed the course (left) and percentage of videos watched by verified learners who haven't completed the course (right)

The date on numbers of lectures watched shows that majority of learners who haven't completed the course watch less than 50% of lecture videos. The median percentages of lecture videos watched for the three runs ranged between 3 – 15%.

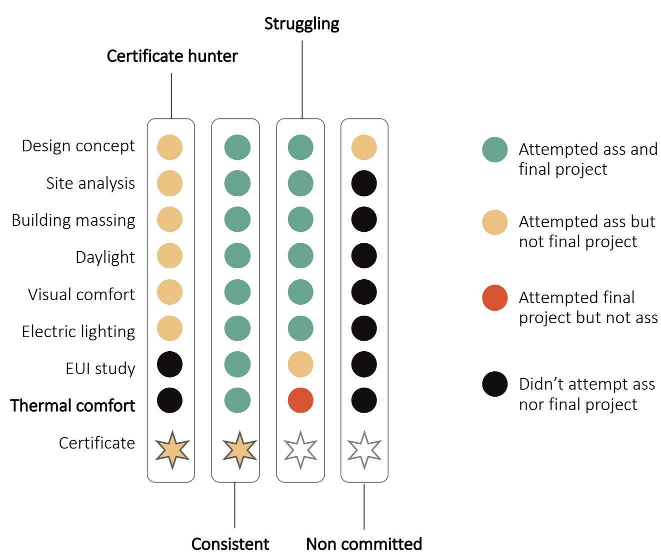
This assessment shows that learners who do not complete the course tend to have a lower engagement with the course. Increased activity level, with a greater number of lecture videos of watched and additional participation in quizzes and discussion boards, has a positive impact on the performance of learners.

6.3.3. The four kinds of learners

A learner is called *active* when they engage with more than half the course contents: watching 50% of lecture videos, completing at least 50% of assignments and submitting the final project. In addition to analyzing learners' overall level of engagement with the course, we assess the success of the MOOC based on learners' performance on the different assignments and final project. Four different kinds of learners are identified based on their engagement with the course and their final grade.

The first kind of learner is a *certificate hunter* who participates just enough to get a passing grade of 60%. In the figure below, the example learner for a *certificate hunter* submitted only 6 of the assignments and not the final project. The second type of learner, is an *active* learner who submits more than half of the assignments, completes the final *non-committed* a passing grade in the course. We call these learners *consistent* learners. The third kind of learner, also an *active* learner, fairly engages with the course by completing most of the assignments and the final project, but was not able to get a passing score despite the effort. We call this type of leaner a *struggling* learner. The fourth type of leaner, *non-committed,* only attempted one or two assignments and had a very low engagement with the course. At the end, we identified four different kinds of learners. Consistent, Non-committed, Certificate Hunter, and Struggling.

This figure below shows how we evaluated the performance of each learner. The dots represent the different sections on the final project and the corresponding assignments. A green dot indicates that the learner has attempted both the assignment and the section on the final project, and a yellow dot means the learner attempted only the assignment. While a red dot means only the section on the final is submitted, a black dot indicates that the learner didn't attempt the assignment nor the section on the final. A golden star at the bottom indicates that the learner has a passing grade for the course, which is 60 out of 100. In the figure, the first two learners, *certificate hunter* and *consistent,* have received certificates while the other two, *struggling* and *non-committed*, didn't get passing grades.



We did similar assessment for all verified learners who participated in the first run (see appendix B). Among the 226 verified learners we studied, 116 leaners or 51%, have submitted the final project. What we found is that 99% of learners who submitted the final project have successfully completed the course, and received a certificate, while only 13% of those who didn't submit the final passed the course. This shows that learners who attempt the final project are more likely to successfully complete the course. As the primary goal of the course is to have as many learners as possible complete the course with a passing grade, the focus of the teaching team shall be supporting the *struggling* learners, who put consistent effort and time but fail to attempt the final project.

6.4. Improving learning success of struggling learners

6.4.1. Challenges of struggling learners

Two primary challenges of struggling learners are identified: time limitation to complete the final project and not having a background in design or related fields.

6.4.2. Deepening **learning** via final projects

The primarily goal is to have learners, verified or audit, go across the finish line with at least the minimum passing grade using accessible and effective content delivery. Beyond mere completion of the course with a passing grade, how do we define learning success for learners? The final project, like the Week 2 assignment discussed in section 6.2, is an open-response, peer-review assignment that is worth 20% of the final grade. It requires learners to apply the various skills and concepts from the course to a building design project. Specifically, learners independently develop an environmental design concept for a 2,500 square meter office startup space located in a city of their choosing.

The purpose of the final project is to enhance learners' **content understanding**. Beyond the basic analysis skills learner's accrued while working on the weekly assignments, the final project requires learners to use findings from their climatic and performance analyses to inform design decisions. A learner can achieve the following three different levels of **learnings**:

- **Basic skills:** Can the learner conduct the required analysis? For example: Can a learner conduct a shading analysis?
- **Content understanding:** Can the learner use the analysis to define design goals and make design decisions? In the above shading exercise example, has the shading study informed building massing of the project?
- **Mastery level:** Finally, does the project exhibit unique and original design feature, beyond the core requirements described in the project brief, to achieve project goals? For example, expanding on the above shading study, the analysis can be used to propose

building integrated shading mechanisms that could reduce cooling needs and improve occupants' comfort.

95% of learners who completed the final project have achieved a passing grade, indicating that completing the final project is a strong indicator that the learner would complete the course successfully. Even though the final project only accounts for 20% of the total grade, it is designed to guide learners use all the analysis skills they learned throughout the course and apply them to create a new building. Completing all section in the final project could indicate that the learner has followed the course thoroughly, and has attempted the assignments.

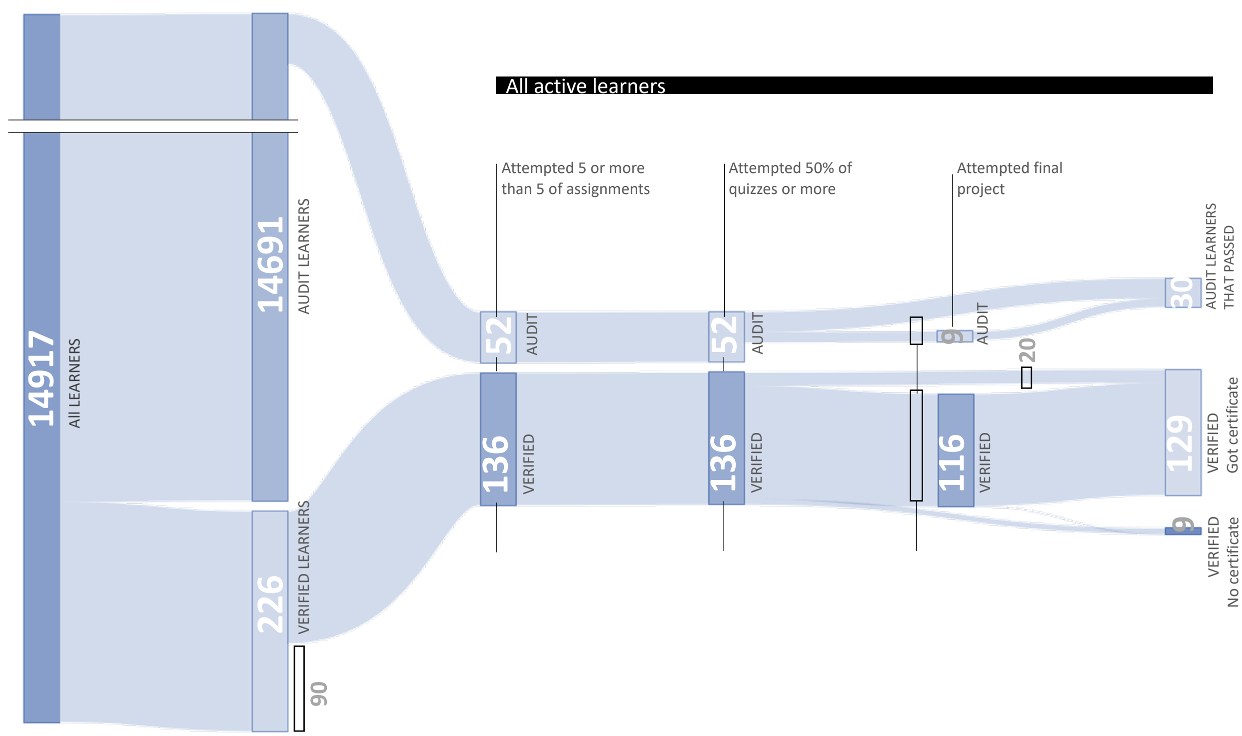


Figure 6.4-1 Active learners in the first MOOC, who participated in 50% of course content and received certificates.

6.4.3. Delivery structure changes

To allow leaners to work on their course project from the bringing of the course, the delivery of the MOOC course can be adjusted so that weekly assignments form different sections of the final project, as shown in the figure below.

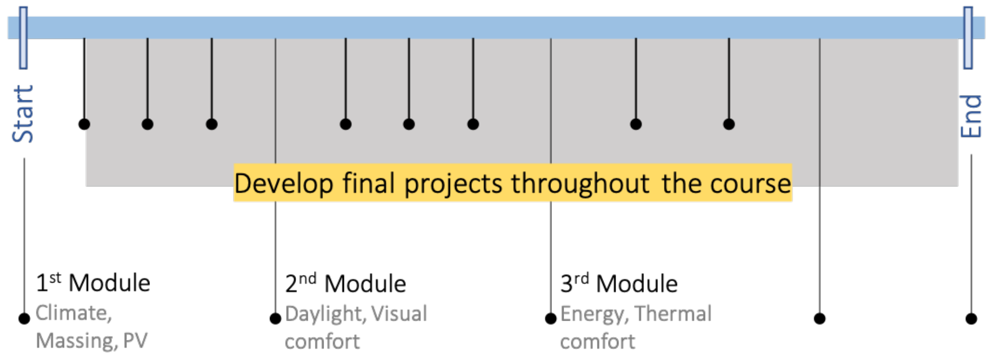


Figure 6.4-2 Course structure adjusted so that students will work on the course project starting from the first week.

6.5. Peer assessments

As discussed in section *6.2. Delivery and Challenges*, the MOOC relies on peer assessments to provide feedback on the final course project. Peer-to-peer review is being used as an alternative to an expert or staff grading for submissions that cannot be computer graded because of the multiple solution nature of the questions. The final project is designed in an open format, and the deliverable is a detailed slide presentation about the startup space, which includes all the details outlined in the rubric below.

6.5.1. Evaluation rubric for peer assessment

Although the deliverable is far more detailed than that of the Week 2 assignment, the streamlined approach to the grading rubric from Week 2 was carried forward so that learners could evaluate the overall quality of peer submissions without necessarily being experts themselves. Rigorous verification of the various analyses and calculations contained in each submission is discouraged; rather, if the required elements are present and there are no egregious errors or omissions, the submission receives full points. For example, under the “Site Analysis” criterion, the peer evaluator selects one of three values:

- 5 out of 5 points: The required elements are included and accurate
- out of 5 points: The required elements are partially included/accurate
- 0 out of 5 points: The required elements are not included

Importantly, text input is required under each criterion so that learners are made aware of which omissions and/or inaccuracies are present. Once learners submit their final project and three required peer evaluations, they receive their final grade and have the opportunity to comment on the helpfulness of the peer reviews. At the conclusion of the final project grading period, the moderators run a report that collects this feedback and review and override grades if there are concerns about the accuracy of the peer evaluations received.

The open-response design project is imbued with the hands-on, in-depth learning objectives of the course. However, having a final project peer-reviewed may raise concerns. To further validate the grading rubric, in 2020, five graduate students from the MIT Architecture department reviewed approximately 20 final projects submitted in the MOOC's June 2020 offering. Their assigned grades and comparison to peer reviews are presented in section 6.5.2.

6.5.2. Comparison of peer-to-peer and expert evaluation

To validate if peer-to-peer evaluations are reliable enough to determine final project grades for a sustainable building design project, we conducted a study comparing scores provided by experts with peer evaluations for 100 final projects submitted during the second MOOC run, administered in 2020 between June 23 and Sept 22. Five experts who have previously taken the residential version of the course at MIT, were involved in this experiment, each grading 20 projects. From the 100 projects, 87 implemented *Track 2* approach to conduct building performance analysis using web-based tools such as DIALux and ClimaPlus. The remaining 13 projects used ClimateStudio for daylight and thermal simulations.

How often did peer reviews differ from expert assessments? We are particularly interested to evaluate if peer and expert assessment for a given project are within an acceptable range. For a peer and expert grades to be considered not significantly different, we have assigned a difference of 5 percentage points as the maximum limit. And, the comparison study shows that projects in this category are 31%. However, the results also show that for majority of projects, 48 out of 100, experts gave grades that are higher by 5 grade points than peer assessments. From this we can conclude that experts tend to give higher grades for projects than peers.

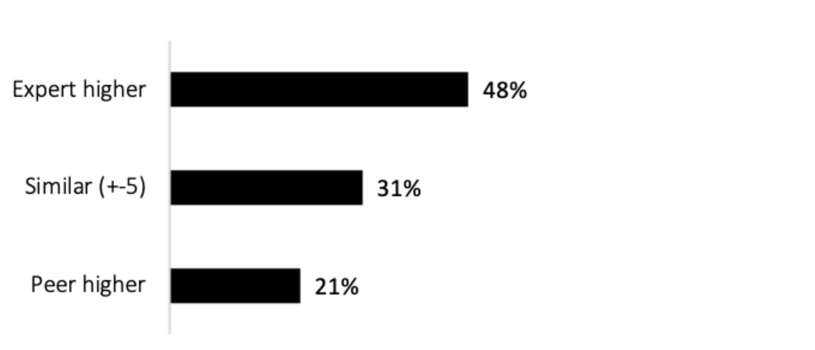


Figure 6.5-1 Number of projects where experts or peers graded a final project higher by more than 5 grade points.

The scatter plot below shows peer and expert grades given for the 100 projects used in this study. In agreement with *Figure 6.5-1*, the plot shows that expert grades tend to be higher than peer grades, and a week positive correlation is observed, given with an R^2 value of 0.4. The teaching team had an expectation for a moderate to strong positive correlation, because prior caution had been taken by carefully simplifying the grading rubric to avoid significant differences from subjective judgements of multiple peer graders. The adjustment was that full or partial grade points were given for each section based on the completeness of the content learner delivered, and not by its correctness (see section 6.2 on delivery methods).

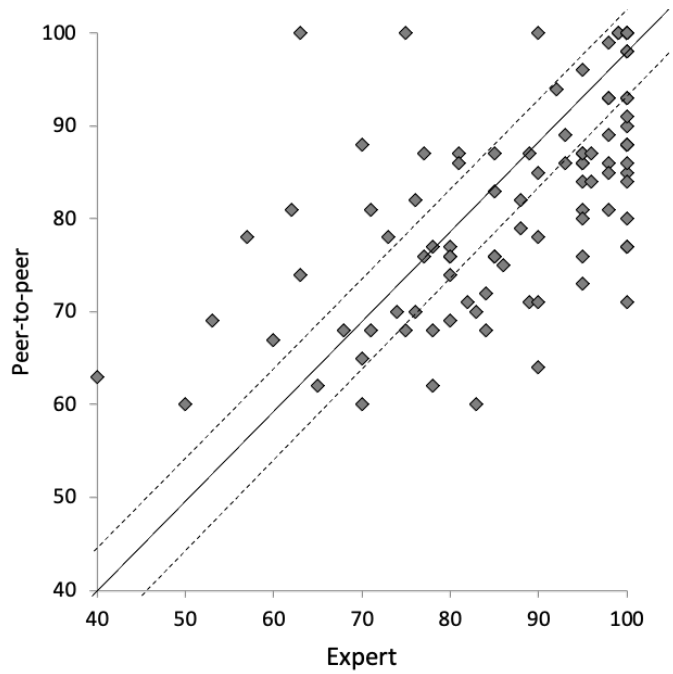


Figure 6.5-2 Peer and expert grades for all 100 projects used in the experiment.

To better understand the reasons behind the weak relationship observed between peer and expert evaluations in this MOOC and to provide recommendations for future runs, we conducted further assessment on projects where large grading gaps are recorded.

When do large differences between peer and expert evaluations happen? Even though experts tended to give higher grades than peers as shown in the figure above, the largest grade point differences between peer and expert assessments occurred when peers graded higher than experts. The figure below shows that in some projects peers have given grades which are higher than expert assessments by 30 grade points and more, but not vise versa.

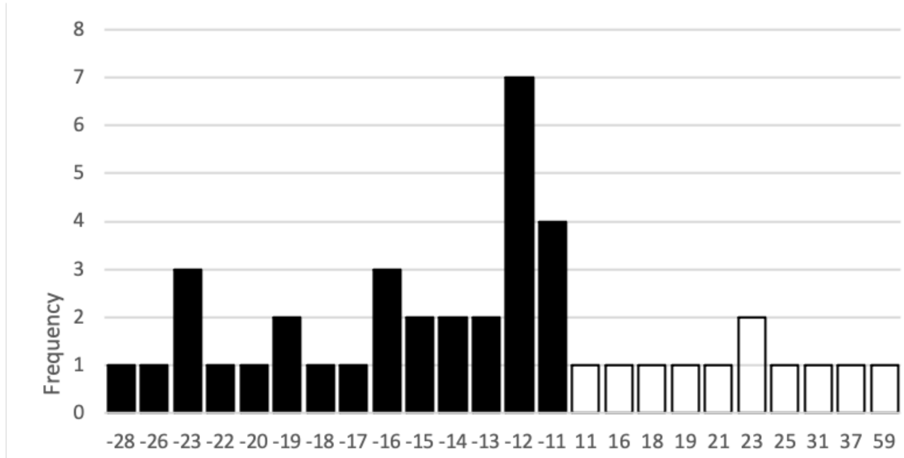


Figure 6.5-3 Selected final projects with grade differences between peer and expert evaluations that are more than 10%

Is there a difference in the distribution of peer and expert grade points? There is at least a difference of 10 percentage points in 49 final projects out of the 100 between peer and expert evaluations. This indicates that there is significant difference between the two evaluation methods for about half of the projects. In addition, total number of projects that were in a mid-range, between 60 and 90 percentage points, are 48 based on expert assessments and 78 based on peer assessments. This shows that peer assessments tended to under-evaluate high performance projects, and over-evaluate week projects.

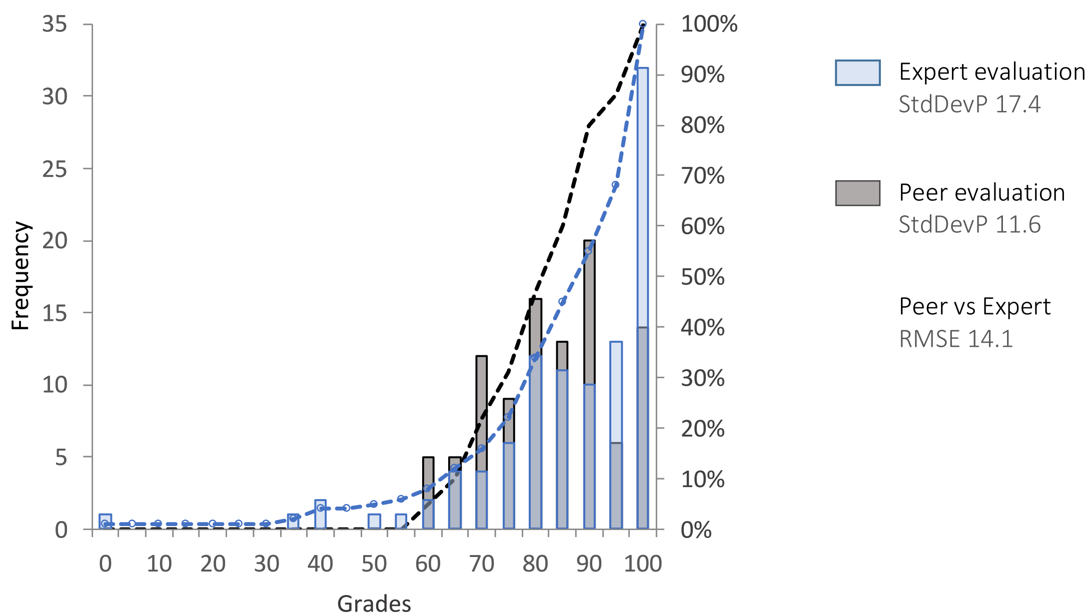


Figure 6.5-4 Histogram of peer and expert evaluations for 100 projects

The 'averaging effect' of peer-to-peer assessment

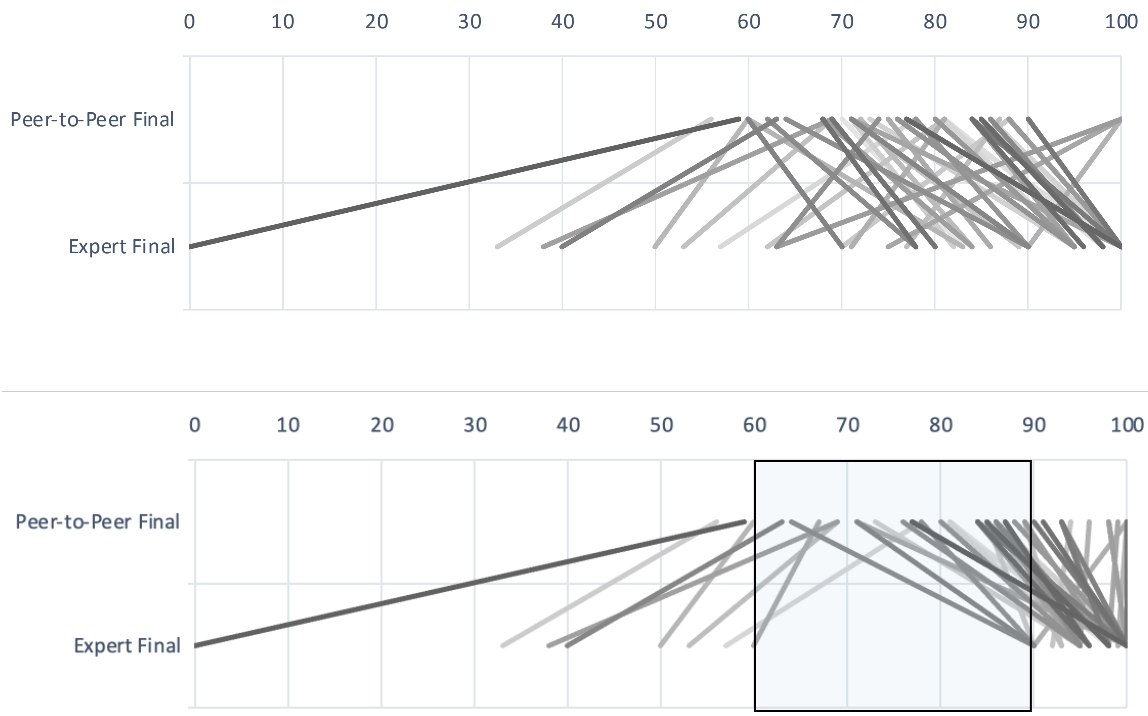


Figure 6.5-5 Peer and expert assessments of projects selected for this experiment: (top) showing projects where the difference between peer and expert evaluations are larger than 10 points and (bottom) only showing projects with expert grades below 60 and above 90.

From the 100 projects studied here, 10% received a 100% grade by peers, 21% received a full score by experts, and only 5% of projects received 100% both by peer and expert evaluation. We selected projects with large variations between peer-to-peer and expert evaluations are recorded for further analysis. Each project is evaluated by two or three peers, and the final peer grade calculated as the average of the three peer assessments.

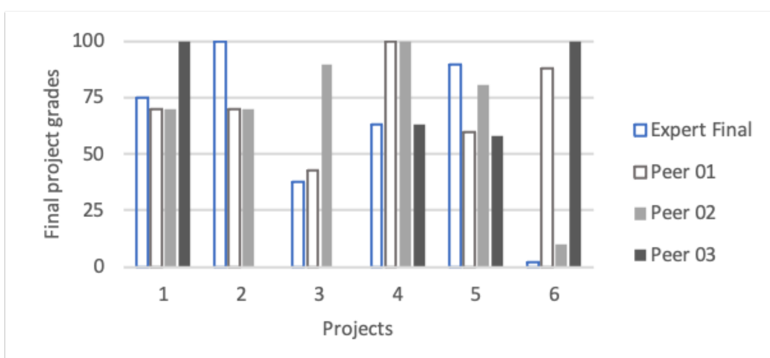
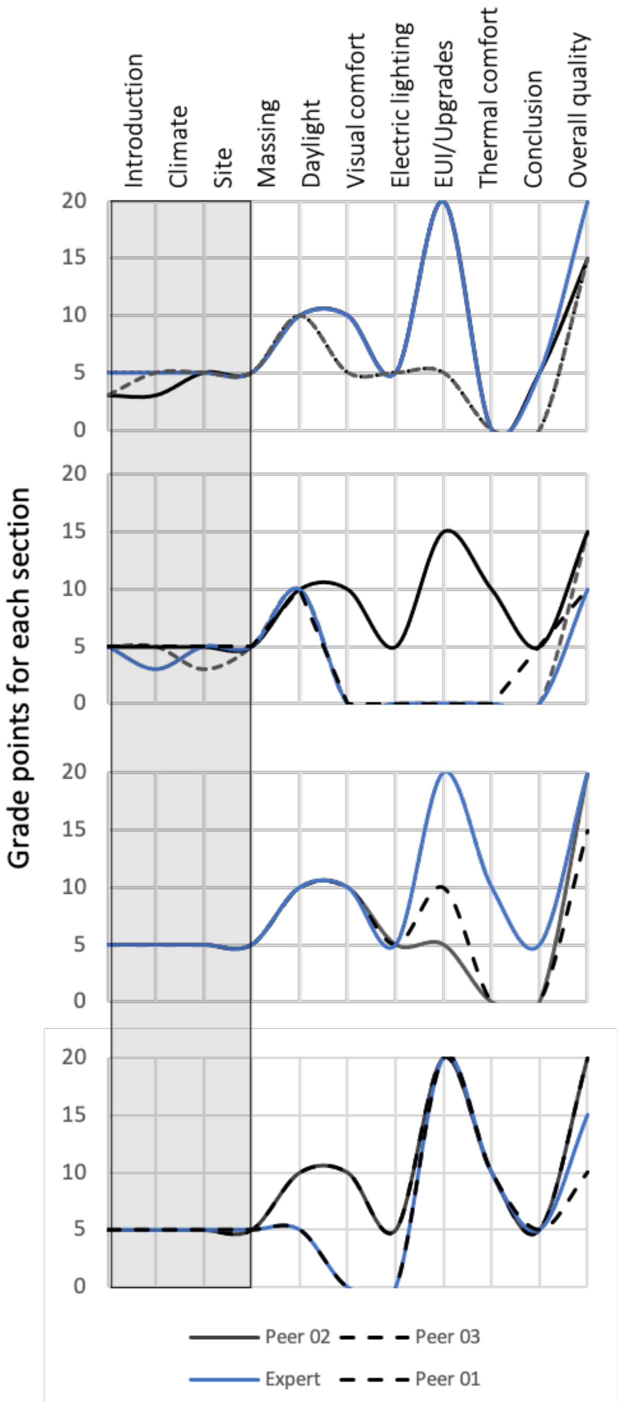


Figure 6.5-6 Selected course projects from the second MOOC, to show the comparison of expert and peer assessments



Selected projects with large differences (between 25 and 40 grade points). Grades are plotted for each section on the final project.

Large differences between graders are observed on the sections of visual comfort, electric lighting, EUI/Upgrades and thermal comfort.

Observed limitations with peer-to-peer evaluations:
Some peers seem to grade without even checking if the leaner has included the required content. We have a case where a peer gave 100% to a project where none of the required contents are submitted.
Grading comments are optional for peer graders. We observed that when peers give comments, they tend to provide better evaluations.

Figure 6.5-7 Final project grade points for different sections for selected projects

The final project has 11 sub-sections that are graded from 5 to 20 grade points. Figure 6.5-7 shows that there are more grading differences between peer and expert assessments in some of the sections.

Cumulative comparison of final project evaluations

Peer-to-peer assessment of verified learners' final project was implemented starting from the second run as the number of verified learners increased by 3.5 folds compared to 222 learners in the first run. In the experiment comparing peer and expert assessments using 100 projects selected from the second run have shown that peer assessments tend to average grade percentages. Following charts compare the distribution of final project grades from the 1st MOOC (expert evaluated), the 2nd MOOC (peer evaluated), and the 3rd MOOC (peer evaluated) to show how peer evaluation affects the overall distribution. We see that in the first run 9% of final projects received grade percentages below 60, 29% between 60 and 90, and the majority, about 71%, received above 90. In comparison, in the second and third runs, the majority of learners – 51% and 53% -- received grades between 60 and 90 grade percentages.

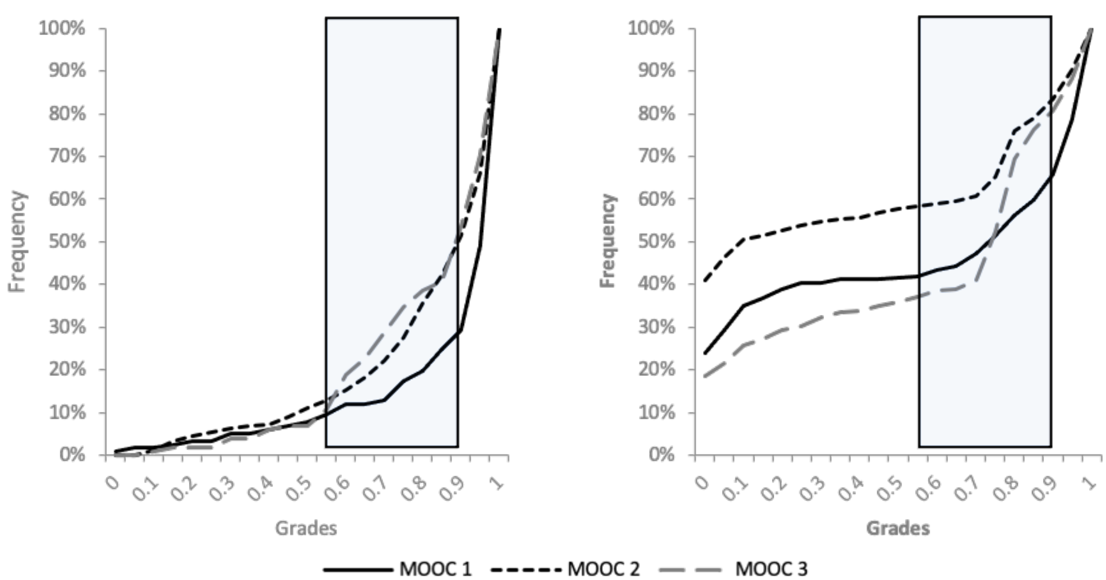


Figure 6.5-8 Distribution of final project grades (left) and overall course grades (right), comparing the three runs

How much does the peer evaluation on the final affect overall grade? The figure above (right) shows final grade of verified learners. In the second and third MOOC a sharp increase is observed between 70 and 80 grade points. This could be the distinction between those who submitted and didn't submit the final project, which carries 20 grade point (30 only in the case of the first run).

To evaluate how the difference between the peer and expert assessments of final projects affected the overall grade, we recalculated the leaners final grades using expert grades for the 100 learners whose final projects are used in this experiment. As shown in the frequency distribution figure below, comparing two possible final grades – when final project is evaluated vs when it is evaluated by peers – the difference between peer and expert evaluations discussed above has little impact on the overall grade of learners. This is the result of the adjustment made on the rubric when peer assessments have been implemented in the second MOOC, that final project accounts of only 20% of the overall grade.

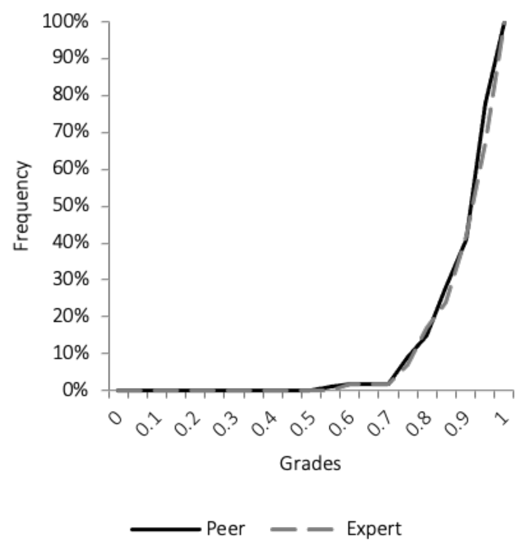


Figure 6.5-9 Frequency distribution of final course grades for the 100 learners in MOOC 2, whose final course projects are evaluated both by peers and experts.

6.6. Conclusions

The analysis on the MOOC course has shown than it is technically feasible to teach actionable sustainable building design concepts to a global audience, by making reliable bioclimatic information available in a clear and intuitive presentation. And, the following main findings and lessons are identified from the analysis.

A funnel effect is observed which favors young learners with some college degree and a background in design related field.

By studying different profiles of learners, we find that time and lack of background in design are the primary challenges faced by struggling learners who couldn't get a passing grade despite their active participation in the course.

Improving peer assessments is important for a new delivery structure where learners would start working on their final projects from the first week. Making peer evaluations reliable helps provide equitable and fair assessment of learners' projects.

The findings suggest that the delivery mythology of the course to be updated to address challenges faced by struggling learners, primarily time to complete the course project. In a bigger scale, there is a need to address challenges of reliably using peer assessments for such design courses, where computer grading is not possible and expert assessments are scalable to thousands of learners.

PART III: CONCLUSIONS

Chapter 8 - Summary and Discussion

8.1 Lessons learned from delivering the MOOC

Considering the broad range of learner's background, we had provided two different tracks for the course as discussed in section 6.2 on delivery method of the MOOC. Close to 80% of learners who submitted their final projects used the second track that is based on the web-app ClimaPlus, creating an opportunity to reach out to many learners regardless of their education background. The goal of the MOOC is to bring as many learners as possible to a mastery level of content understanding so that they can design a sustainable building using reliable bioclimatic information. The course is structured to guide learners from learning, to applying, to creating sustainable building concepts and strategies.

What is the evidence for learner's content understanding? This is particularly a useful question for online educators, where the learning process is one way – learners depend on pre-created contents and have limited opportunity to engage live with the instructor. Honing *basic skills* and fostering *content understanding* of leaners are the core mechanics of the MOOC. Final projects that demonstrate originality show a high-level performance. Most of the final projects that exhibit this level of quality are done by learners who have a design background. Even though the goal of the course is not to reach architectural design, and it attracts learners with and without design backgrounds, learners with some prior education in building design would have a better advantage to deliver a high-quality project.

How impactful was the MOOC course? From the 1,261 verified learners across the three runs, 338 learners have shared their feedback on a post-survey after completing their final project. 76% said they are "extremely likely" to apply the skills and tools honed in the course, while 22% said they are "somewhat" likely to apply. For a survey question "Which do you expect to use most frequently?", 40% said they would use Climate Studio/Diva while 82% said they will use browser-based ClimaPlus.

Challenges of delivering a design course with open-ended assignments

One of the main challenges when delivering a design course for a large and diverse audience is that assignments and final projects are mostly open ended, and evaluations would not be straight forward. This study aimed to showcase an example of how a MOOC course with open ended assignments can be administered and if peer-to-peer evaluations are reliable enough to replace expert or staff grading for large classes with thousands of learners.

The experimental study presented in section *6.5. Peer assessments* has shown that the peer assessment approach used in the MOOC, has not significantly affected the overall course grades of learners despite the limitations discussed in comparison to expert evaluations. This is primary because peer evaluation is used for the final project that accounts to 20% of overall grade. However, the recommendation drawn to support struggling learners who are not able to complete the course requires adjustment on course delivery, that would require peer-assessments to be used throughout the course, so that learners could develop their project earlier in the course in a form of weekly assignments. This requires course team to implement strategies to improve reliability of peer evaluation, to guarantee fair and equitable assessments of learners' performance.

Recommendations to improve peer assessments

Only peer graders who have submitted a final project are assigned to grade other projects, and this would guarantee that the peer grader has prior exposure to the project requirements. However, we learned that peer graders might be biased for multiple reasons and their grades might over or under estimate the score the project deserves, according to a large-scale study on multiple MOOCs (Piech et al. 2013).

The study has shown that some peer graders tend to give full score, without properly checking if the learner has submitted all required sections. Peer graders shall be required to provide comments to justify their assessments. An extra level of solution that can be implemented by the course team to filter peer evaluation with a 100% score and re-evaluate the project.

Grading peer-grading: reinforcing formative learning via peer assessment

Grading peer grading is identified as a solution to incentive peers to willingly engage in peer-to-peer grading, and potentially improve the quality of peer assessments. Other studies have identified two main benefits of the peer assessments to learners: Another peer assessment experiment will be planned in future MOOC runs to study the formative and summative values of peer assessments.

Evaluation rubrics rewarding content understanding

One strategy to evaluate the success of the online course is to verify, when learners compete the course or pass the class, if they have well understood core concepts and are able to apply them in a real-world project. This is especially true for a design related course such as this MOOC. The project evaluation rubric shall reward content understanding of learners and not just analysis skills to create multiple charts and attractive graphics.

A learner's project could react to the analysis conducted via simulations or calculations within a particular topic, such as building massing design, daylight study or energy informing design decisions. Additionally, the learner's content understanding across topics is demonstrated when design decisions in one section are affected by the findings from another section. For example, the massing of a building could be primarily created to provide daylight to all regularly occupied spaces. However, if the energy analysis suggests that there is high cooling demand due to high solar heat gain inside the building, seeking a solution by going back to the massing design to reduce direct exposure to solar gain from the immediate surrounding is a cross-connection between two topics.

8.2 Research Outlook

8.2.1 Implementing interventions to support MOOC learners

A statistical approach to improving peer assessment

In agreement with our finding, according to a study on Coursera's platform that compared peer-to-peer assessments with calibrated, statistical grade predictions for courses in humanities and social science, the success of a peer grading relied on a couple of factors (Piech et al. 2013): . The study reported some trends in peer evaluations, using thousands of peer evaluations on 6 different course runs, and presented a statistical approach to peer-grading, using educational data mining. A similar approach can be explored to bring equity and fairness in peer assessments of design courses.

Impact assessment in the context MOOC learners

Impact assessment of this online course, particularly in the developing world where the largest population growth and energy demand is expected would be part of future research. By using anonymized data from the edX platform, and thousands of survey responses provided by learners before, during and after taking the course, the study aims to gauge the impact of the course on learners, either professionally or personally. Other methodologies will be explored to quantify impact – both in building construction and policies – of having more designers and professionals who participated in a sustainable building design course.

8.2.2 Application of the climabox approach

Quick simulations are useful to run and compare multiple scenarios. The climabox approach is being used to study the implication of current AC adoptions and draw recommendations to address challenges of temperature increase under global warming.

Preliminary findings of this study on the largest 30 cities of Africa based on calculated numbers of discomfort hours and median household income show some cities have higher health risk due to temperature increase from global warming. Building interventions to reduce cooling and heating, by predicting energy demand and comfort conditions based on temperature distributions.

In future work, the climabox approach will be implemented to evaluate and formulate carbon emission reduction policies. Additionally, it will be used to evaluate new and upgraded technologies that are designed to enhance the performance of buildings.

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Appendix A

Table 1: Presentation Content Rubric

# of slides	Points	Content	Description
3	5: All points were included 3: Missing points of intro 0: No introduction	**Introduction** - Introduce yourselves and your design philosophy. - Show one or more precedents. - What is your target Energy Use Intensity (EUI) target? For reference: Assignment 1	Describe the main qualities that you would like your building to exhibit, such as being as energy efficient as possible, providing good daylighting for all work spaces, etc. Your specific goals are up to you, but you should make sure to include some of the elements covered in class. For the EUI target level, refer to datasets such as the EPA Target Finder or comparable web sites for different countries. ***For all energy simulations make sure that you understand whether you are calculating site or source EUI. Explain where your target levels come from.**
1-2	5: Temp. profiles, radiation, and effect on building included 3: Some climate analysis included 0: None included	**Climate Analysis** Discuss your local climate (temperature profiles, solar radiation, etc.), and describe how your building design concepts react to ambient environmental conditions. Be specific. If you show any graphs or figures they should directly relate to your site and design.	Use figures from ClimaPlus or comparable programs to support your claims about the local climate.
1-2	5: Massing model and direct shading study included 3: Partial accuracy/inclusion 0: None included	**Site Analysis** Discuss your site using, for example, Google Maps, a massing model of surrounding buildings, and a direct shading study. Discuss how your building massing will react to this analysis. Depending on the climate, you may prefer to shade your building with neighboring structures or not. For reference: Assignment 2	Create a massing model and conduct a direct shading study using the same workflow as for the Shading Study in Week 2. *****Please note that if you are following Track 1, using ClimaPlus, your building or section of building, as was done with the E-shaped building in your weekly assignments, should be a rectangle. ***Remember to include neighboring buildings in your shading and daylight analysis.**

1-3	5: all 3 building massing models included 3: Partial accuracy/inclusion • 0: No massing model	**Building Massing** Show three possible massing models of your building design. The models should be logically placed on your site according to the reaction to your previous daylighting analysis. For reference: Assignment 5	Sketch your massing model on paper or add it to your CAD model. In the latter case, you may also want to show any self-shading study during the Winter and Summer solstice, if applicable. ***All plans and perspectives must have a North-facing arrow.**
1	10: all 3 daylight % included 5: Partial accuracy/inclusion 0: No daylight %s	**Daylight Availability** Calculate the percentage of daylit area for each of your three massing proposals and pick one of your options for analysis going forward. For reference: Assignment 5	Use either the rules of thumb approach from week 5 – Daylight Availability or use a simulation program such as DIVA-for-Rhino or ClimateStudio to calculate spatial daylight autonomy results.
1-2	10: Correctly determined hours of glare on workspace 5: Partial accuracy/inclusion 0: Glare detection not included	**Visual Comfort** Estimate the occurrence of glare for your final design from the previous step. For reference: Assignment 6	You have multiple options to evaluate glare. You can either use a sun path diagram to determine when direct sunlight will be incident on key workplaces (Assignment 6), and/or you can use a more advanced simulation program to determine the annual occurrence of glare at any workspace. You could even start adding dynamic shading systems, such as blinds or switchable glazing units, to prevent glare. ***For Daylight Glare Probability (DGP) simulations make sure that the view position is representative of where people usually are. It can be helpful to show a plan with the viewpoint and direction on it. This step has been largely automated in ClimateStudio.**
1-2	5: Reports luminaire type and required LPD 3: Partial accuracy/inclusion 0: Electric lighting not included	**Electric Lighting** Select a typical area within your building, select a luminaire type and calculate the required lighting power density to maintain 300lux from electric lighting for all regularly occupied areas	Again, you may either use the simplified method from week 6's assignment to pick a luminaire type and calculate the resulting lighting power density. Or, you may use a more advanced lighting design software and calculate illuminance distributions along with select

		For reference: Assignment 6	perspective views from different lighting configurations. ***All figures need correct units and legends (cd/m² and lux are not the same; kWh or kWh/m²; kWh or BTU)**
1 slide per measure	Up to 20 pts; 5 pts for each upgrade 0: No upgrades applied	**EUI Study** Conduct an EUI in which you successively add different design measures to your building including. These measures may include reduced internal gains, upgraded building envelop components and photovoltaics. For reference: Assignment 7	You may either use ClimaPlus or a more advanced thermal simulation program to calculate annual energy use for heating, lighting cooling and equipment for your building. Summarize your results as in week 7. Feel free to also add carbon emissions and operational energy costs to your analysis.
1	10: Explanation and overheated hours/results included 5: Missing explanation or hours/results 0: No thermal comfort analysis	**Thermal Comfort** Explain if you want your building to be naturally ventilated or not. Show the hours of overheating of the course of the year and discuss your results. For reference: Assignment 3 and Assignment 8	Use ClimaPlus or a more advanced thermal simulation program to discuss indoor temperature distributions in key zones within your building. Please discuss whether you think that thermal comfort conditions in your building will be adequate.
1	5: Conclusion 0: No conclusion	**Concluding Thoughts** Summarize your results and share some final thoughts on your building design.	
1		**Perspective View (optional)** Show inside and outside perspectives of your final design.	Provide a hand sketch or 3d perspective rendering software of your final design.

Table 2: Rubric

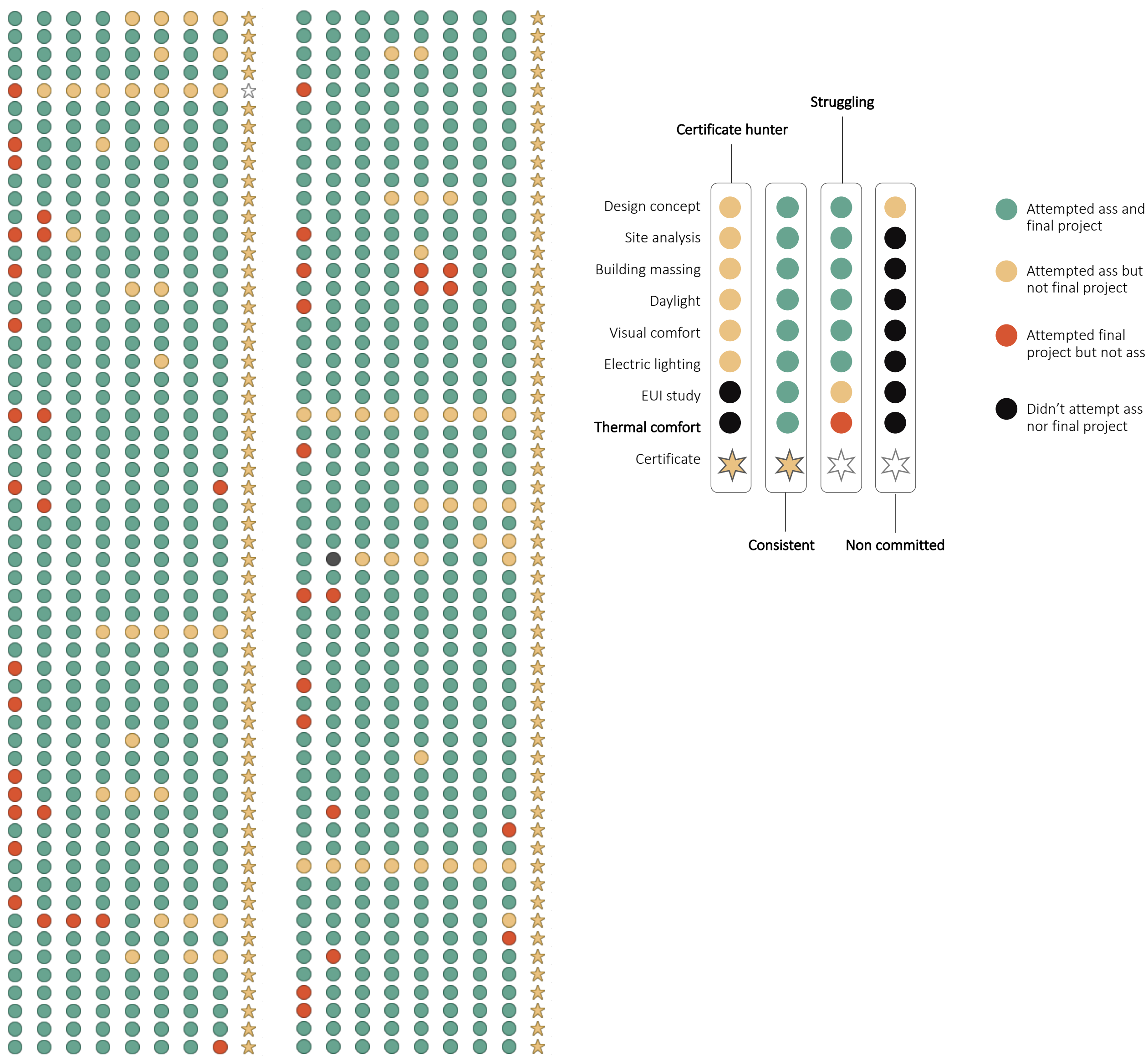
Presentation Content	80 points
Overall Clarity, Visual Appeal, and Originality	20 points

Your final project is worth 20% of your total course grade.

Appendix B

The following figures show the performance of learners from the 1st MOOC run using the methodology laid out in section 6.3 of this thesis.

(i) 116 Verified learners who completed the final project



(ii) 110 Verified learners who didn't complete the final project