DIGITIZING VERNACULAR NIGERIAN BAMBOO SCREENS: A GENETIC OPTIMIZATION FRAMEWORK ANALYZING ENVIRONMENTAL PERFORMANCE AND ECONOMIC AFFORDABILITY

by

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Architecture

Charlotte

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Approved by:

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ABSTRACT

IJECHUKWUAMAKA OLUWAPELUMI PATTERSON. Digitizing Vernacular Nigerian Bamboo Screens: A Genetic Optimization Framework Analyzing Environmental Performance and Economic Affordability. (Under the direction of JEFFERSON ELLINGER)

The pressures of rapid urbanization and climate change are severely affecting cities such as Lagos, Nigeria. Failures of modern construction practices to accommodate various impacts of local climate conditions as well as traditional construction techniques and materials are magnified by the bi-directional relationship between environmental challenges and economic conditions [1]. As seen in government-targeted squatter homes and slum communities, poor methodology for vernacular construction also emphasizes this interrelation.

With the right application, the strengths of vernacular architecture—the result of hundreds of years of optimization—can be utilized to provide a comfortable shelter in a local climate using available materials and known construction technologies [2]. This thesis proposes a framework for designing and optimizing generated adaptations of colloquial bamboo screen systems for effective application in Lagos. The optimization framework developed employs computational design methods and tools as leverage to the complex challenge involving material technology, costs, and environmental performance factors. The framework is designed to be used for future externally prospected vernacular solutions of building components with the same implications in specific contexts. In this thesis, a proof-of-concept study is conducted employing genetic algorithms in the developed design program to accelerate the digital resolve. The framework is created to effectively inform stakeholders to embrace local traditions for contemporary energy goals by providing digestible means for rigorous quantitative and quantitative analysis. The results indicate that improved environmental performance and cost can be achieved by utilizing the developed generative optimization framework, creating scalable affordable vernacular solutions that increase comfort and quality of life in challenged communities.

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DEDICATION

This is dedicated to the love of my life, my friend, my Lord, and Savior Jesus Christ. Thank you for ordering my steps and strengthening me. For your overwhelming peace that surpasses all understanding, your favor, mercy, and the grace to do all things through you who has called me to do them. To my amazing husband, Eddie Lee Patterson Jr. for your continued holistic support, sacrifices, labor of love, understanding, and patience. Many thanks for holding it down and taking care of me so I can succeed, I couldn't have done this without you at all. To my parents Pastors Dupsy and Jackie Omotosho, thanks for your prayers and never-ceasing encouragement and inspiration, for answering my panicked calls in the middle of the night and speaking peace over and strength into me. To my siblings Mayowa, Joshua, Kiki, and late sister Odelia thank you, thank you, thank you, you inspire me. To all that encouraged me in any way, Bless you. Thank you to Have Life, and the H.U.G.S department for holding me up. Especially to my Pastors Dr.Shomari and Jacque White for praying me through, teaching me the importance of a healthy mind, encouraging the unorthodox pursuit of academia as educators yourself, and for your obedience in creating welcome spaces for my restoration, and refreshing. You have recharged me each week to push through till the end and to do so in excellence.

TABLE OF CONTENTS

ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
DEDICATION	v
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF ABBREVIATIONS	xi
CHAPTER 1: INTRODUCTION	1
1.1 CONTEXT AND PROBLEM	1
1.2 COMPUTATIONAL LEVERAGE	2
CHAPTER 2: BACKGROUND	10
2.1 CLIMATE AND ECONOMY	10
2.2 VERNACULAR VS CONTEMPORARY ARCHITECTURE	13
2.3 LAGOS, NIGERIA: URBAN SPRAWL, ECONOMY, AND CLIMATE	17
CHAPTER 3: METHODOLOGY	26
3.1 OVERVIEW	26
3.2 PROOF OF CONCEPT MODEL	28
3.3 PORTION 1: GEOMETRIC PARAMETRIC MODEL DEVELOPMENT	31
3.4 PORTION 2: SIMULATIONS & CALCULATIONS	38
3.4 PORTION 3: OPTIMIZATION	47
3.5 DATA VISUALIZATION & RECORDING	53
CHAPTER 4. RESULTS	56
CHAPTER 5: CONCLUSION	66
5.1 SUMMARY OF TAKEAWAYS	66
5.2 FUTURE WORKS	73
REFERENCES	75

LIST OF TABLES

TABLE 1: Passive Vernacular Studies 5

TABLE 2: Data of Nigerian Economy 18

TABLE 3: Vernacular Climatic Responsive Analysis 23

TABLE 4: Pre-Study Screen Results 36

TABLE 5: Denoted Validations for Simulation Software Selection 39

TABLE 6: Recommended Illuminance 43

TABLE 8: Contemporary Base Case vs Most Optimal Vernacular 68

TABLE 9: Proof of Concept Indicator Evaluation 72

TABLE 10: Digitizing Vernacular Bamboo Screens Framework Future Work 73

LIST OF FIGURES

FIGURE 0.1: Comparison of Vernacular Aperture Analysis Study Approaches 6

FIGURE 0.2: Digital Methodology: Comparisons of Designer Workflows 7

FIGURE 0.3: Parametric Design 8

FIGURE 0.4: Design Optimization Flow 8

FIGURE 0.5: Generative Design Process 8

FIGURE 0.6: Evolutionary Computing Genetic Algorithms Overview 9

FIGURE 0.7: Evolutionary Computing Biological Evolution Mechanisms 9

FIGURE 1.0: Spatial Pattern of Years Exceeding 2°C Warming 11

FIGURE 1.1: Environmental Kuznets (EK) Curve 12

FIGURE 1.2: Income and Climate Change Loop 12

FIGURE 1.3: Regional Impacts, Vulnerability, and Adaptive Capacity 13

FIGURE 4: Then and Now 14

FIGURE 4.5: Historical Vernacular 15

FIGURE 5: Lesson from Traditional Architecture 16

FIGURE 6. Lessons From Traditional Architecture 16

FIGURE 7: Internationalism Cultivating Global Urban Sprawl 17

FIGURE 7.5: Nigerian Urban Sprawl Compilation 20

FIGURE 8: Nigerian Per Capita Income 2016 19

FIGURE 8.5: Lagos Turns 50 21

FIGURE 9: Demolished Squatter Settlement 21

FIGURE 9.5: Nigerian Economy Non-Agricultural Workers 2016 20

FIGURE 10: Nigerian Climate Conditions Compiled A 22

FIGURE 10: Nigerian Climate Conditions Compiled B 22

FIGURE 11: Nigerian Vernacular Systems 24

FIGURE 12: Nigerian Bamboo Prevalence 24

FIGURE 13: 48 - Hour Bamboo Bungalow 25

FIGURE 14: Architecture of Demas Nwoko 25

FIGURE 15: Nigerian Bamboo Scaffolding 25

FIGURE 16: Nigerian Vernaculars 25

FIGURE 17: Digitizing Nigerian Bamboo Screen Thesis Goals 27

FIGURE 18: Proof of Concept Optimization Framework Flow & Methodology 27

FIGURE 19: Proof of Concept Digital Computational Tool Software Architecture 28

FIGURE 20: POC - GP Model Variable – Parameter Derivation & Definition 29

FIGURE 20: POC - GP Model Variable – Parameter Derivation & Definition 30

FIGURE 21.0: POC – GP Model Final Geometry & Façade Apertures 32

FIGURE 21.1: POC – GP Model Variable Screen Component Derivation 32

FIGURE 21.2: Pre – Study for GP Model Variable: POC Screen Type & Configuration 33

FIGURE 21.2: Pre – Study for GP Model Variable: POC Screen Type & Configuration 34

FIGURE 21.2: Pre – Study for GP Model Variable: POC Screen Type & Configuration 35

FIGURE 21.3: GP Model Variable Screen Component Definition Workflow 37

FIGURE 21.4: POC – GP Model Material Cost Defined 37

FIGURE 23: POC – GP Model CS Simulations Settings 41

FIGURE 23.2: POC – GP Model into Simulations & Calculations Workflow 42

FIGURE 24.0: POC – GP Model Daylight Illuminance Defined 45

FIGURE 24.1 GP – Model Radiation Defined 46

FIGURE 24.2 POC – GP Model Energy Cost Defined 47

FIGURE 25: Pareto Principle 48

FIGURE 25.5: Figure of Tables Comparing Optimization Algorithms 49

FIGURE 26: Optimization HypE Algorithmic Loop Detail 50

FIGURE 27: POC – Algorithm Settings & Displays 52

FIGURE 28: POC - A&B Solution Selection Workflows 53

FIGURE 29: Numerical Data Records 54

FIGURE 30: Graphical Data Records 55

FIGURE 31: Solutions Data: 31.1, 31.2 59

FIGURE 31: Solutions Data: 31.3, 31.4 60

FIGURE 31: Solutions Data: 31.5, 31.6 61

FIGURE 32: Elite: Most Optimal: Solutions to Design Problem 62

FIGURE 33: Most Optimal: 33.a 63

FIGURE 33: Most Optimal: 33.b 64

FIGURE 33: Most Optimal: 33.b 65

FIGURE 33: Most Optimal: 33.c 65

FIGURE 33.5: Contemporary Base Case vs Most Optimal 68

FIGURE 33.6: Optimization Validations 69

FIGURE 34: Framework Relationships 71

LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ANYSYS	Analysis Software (Mechanical Finite Element)
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BNRCC	Building Nigeria's Response to Climate Change
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamic
CMIP6	Coupled Model Intercomparison Project
CRU	Climate Research Unit
DOE	Department of Energy
EK Curve	Environmental Kuznets Curve
EPW	EnergyPlus Weather File
FEA	Finite Element Analysis
GA	Genetic Algorithms
GH	Grasshopper parametric modeling program
IGDB	International Glazing Database
IPC	Income Per Capita
IPCC	Intergovernmental Panel on Climate Change
LEED v4	Leadership in Energy and Environmental Design version 4
LUX	Daylighting Illuminance
NASA	National Aeronautics and Space Administration
NG	Nigeria
NO2	Nitrogen Dioxide

NURBS	Nonuniform Rational B-splines
OECD	Organization for Economic Co-operation and Development
POC	Proof of Concept
POP	Population
RHINO	Rhinoceros 3dm Modeling software
sDA	Spatial Daylight Autonomy
SO2	Sulfur dioxide
SPM	Emission Type Suspended Particle Matter
UI	User Interface
UNCHS	United Nations Centre for Human Settlements
UN-HABITAT	The United Nations - Habitat
WB	World Bank

CHAPTER 1: INTRODUCTION

1.1 CONTEXT AND PROBLEM

There is an evident global climate challenge with adverse effects on communities, especially those in less developed nations (*Figure 1.0*). These regions are impacted by interrelated causes of the housing affordability crisis including bi-directional climate and economic conditions, as well as urban sprawl [3, 4, 5, 6, 7, 8, 9, 10, 11]. A primary reason is the cost of adaptation for effective climate response. There are varying measures of conflict between likely regional impacts of climate change versus vulnerability to the impact with the capacity to adapt *(Figure 1.3)*. Vernacular implementations have been proven to be a method of mitigation but the means to develop the best strategy can be constrained by the required cognitive load to design and the cost and time of design validation in operation. Various reference studies have resolved the negative implications of improper vernacular techniques and-or modern architectural building systems have been analyzed and derived from. Some of the investigative research exhibits new vernacular typologies, case-based material technology applications, and conducted innovative means of comparative analysis (*Table 1, Figure 0.1)*. Inherently, traditional systems provide a comfortable shelter as the result of years of optimization [2]. Optimization is the key to the process of solution development [12, 13].

This thesis generates and applies a streamlined method for the search for the right configuration of local design strategies resulting in comfortable environments that are sustainable. The simplified methodology also tests the effectiveness of a specified configured element. Although realized physical application is out of scope for this study, the intent in mind for the resulting element; a configured bamboo shading screen, is that it could be administered to up-fit existing construction, or as a component of a propositional structure. Scalable problem mitigation is achieved via a proof-of-concept study utilizing Lagos Nigeria as the place of investigative focus and hypothetical application. The nation’s narrative highlights interrelated climatic and economic affordability issues. The envisioned resolve is significant in its address to the concerns of both underprivileged inhabitants and the local regulatory governing often conflicting within these communities. There is lacking an experimental method to quickly simulate manipulated deployments of a vernacular solution to address the nation's needs with digestible means to rigorous quantitative analysis.

1.2 COMPUTATIONAL LEVERAGE

The determined mode of investigation is a computed digital format. Representational modeling and simulations are more efficient than solely fabricated iterations tested through physical experiments (*Figure 0.1*). Factors and characteristics from the context are derived to computationally form the well-defined design problem addressing climate change remitting adverse effects. The selection of the type of aperture screen to optimally generate, the model constraints, and both fixed as well as dynamic variables are determined as they relate to the design problem and the efficiency the of study method. Even in the digital realm the workflow and the tools must be carefully designed. A designer could traditionally model each individual iteration utilizing CAD-based or NURBS-based 3d graphical modeling software or BIM software. However, the task would be arduous and labor intensive and the range of tested designs would be significantly limited. The solution to this development challenge is the utilization of parametric modeling tools, especially visual programming languages and environments that integrate with the geometric 3d modeling digital environments. Parametric design is a method in a 3d modeling process, it utilizes an algorithmic approach to manipulate model geometry forms & elements when a rule or parameter value is modified in the definition. It creates form via computation to develop complex architectural designs and structures (*Figure 0.3)*. Yet still, the ability to change the form of a model geometry simultaneous to the modification of some measurable value requires exceptional efforts of manual labor. In this case, similar implications as the prior scenario would emerge. Instead of being based singularly on the desired results and volume of solutions, the process would be determined by the required laborious capabilities of the designer in iterating through the parameterized constraints for design solutions (*Figure 0.2*).

As applied to this thesis, the resolution to the abovementioned workflow challenge is found in developing a generative script in the parametric visual programming interface of the digitized model. "Compared with traditional top-down design approaches, generative design addresses design problems by using a bottom-up paradigm" [14]. Generative design is an iterative design exploration process that automates the outputting of a specific number of solutions meeting specific criteria, constraints, and rules (*Figure 0.5)*. For the design problem of this study, an output of all possible solutions would be computationally expensive, requiring extensive processing power. The benefit here would be the provision of an increased volume of output. Within a program, the initiation of optimization decreases the computational expenses (required power and time) for the task. For a series of output results to be specified for the application they must evolve to a good, if not optimal resolution. Optimization engines deploy algorithms to tune artificial productions toward the attainment of certain goals and criteria, not just parametric constraints (*Figure 0.4)*. The selection of the best solutions out of the hundreds or thousands that may be developed by the intelligence aid streamlines the evaluation and selection of the user. The algorithm applied for this optimization study is evolutionary computation's genetic algorithms (*Figure 0.6*). GAs are problem-solving techniques of population-based trial and error arithmetic functions to support the generation & selection of the optimal design. They are metaheuristics but utilize some form of stochastic searching methods that mimic the biological evolution mechanisms and social behaviors of species (*Figure 0.7*), [12, 13, 19]. The evaluation and validation of the configured models by feature for goal attainment utilize energy model simulators that reflect real-world conditions, input the appropriate data and project relatively accurate feedback to the integrated digital landscape. The full quantitative and qualitative results of the framework outputs can be visually displayed, saved, and data recorded for further use.

As a design development aid, AI maximizes the leveraging opportunities that computation brings to complex problem-solving. The finalized complexity of factors for proof of concept involves some aspects of material and material demand, cost of construction, and the relationships of those variables with environmental performance goals reflected in building utility costs saved. Simulation software programs are utilized to model and imitate real-world systems and processes with virtual representations analyzed and predicted with arithmetic algorithms. Simulations are used to predict the behavior of the system under different conditions. According to OpenAI's ChatGPT, simulations use computer-aided design (CAD) software, finite element analysis (FEA) tools, and Monte Carlo simulation software, all of which are employed in this study. The means of developing a framework for which the design problem can be processed and resolved required geometric modeling, parametric visual programming tools, and generative components in congruence with the selected optimization engine components fed by simulation software as a cohesive computational design script. This simplified framework develops constituents of climate-adaptive, economically affordable buildings. The streamlined composition of the framework itself accelerates the digitization of resolve to inform designers, architects, developers, and stakeholders in a fulfilling way; equipping all to embrace local traditions to meet contemporary energy goals and remit the related challenges within a specified similar context.

Table 1. Passive Vernacular Studies

Study	Climate	Focus	Method	Synopsis of Findings
[15]	Temperate Monsoon (Tropical)	Analysis of four typical traditional vernacular dwellings & components: dooryard, the structure of the double-pitched roof and the eaves, by the measurements of temperature, wind velocity, & principles at Wannan area in summer.	Field measurements of the thermal environment parameters & a long-term auto-recorder of the indoor & outdoor temperature	Revealed sun shading & insulation are of great importance, natural ventilation is considered as an auxiliary approach. Strategy of ventilation design restrains at daytime & boost at night
[16]	Coastal Tropical	Solar passive techniques (orientation of building, internal arrangement of spaces, internal courtyard inclusion, use of locally available materials & special methods of construction) in Vernacular buildings in Tamil Nadu India in a year	Qualitative analysis of Kerala vernacular passive env. control system for indoor comfort in residences. Quanitative field study	Confirmed that passive environment control system employed in Kerala vernacular architecture is highly effective in providing thermal comfort indoors in all seasons.
[17]	Coastal Tropical	Solar passive techniques in Vernacular buildings vs Modern buildings in Tamil Nadu India in the summer	Comparative investigation. continuous monitoring in-out conditions of both using custom made instrument "Architectural Evaluation System".	Results reveal: efficient passive & natural control system exists in Kerala trad. architecture providing a comfortable indoor environ. irrespective of the outdoor climatic conditions
[18]	Tropical Monsoon, Tropical Savanna, Semi-arid	Vernaclar material to mitigate diverse natural hazards. investigates a material which can be substituted for wood or steel in construction in Nigeria.	Study examines bamboo & its environmental benefits, its properties & qualities including accessibility & impacts on the environment (no experiment)	Concludes bamboo use as a substitute material for construction in Nigeria for sustainable environment. Further research should be conducted on characteristic & properties of the species
[2]	Subtropical Monsoon, Warm Temperate, Cool Temperate, Alpine	Use solar passive measures to achieve thermal comfort conditions in traditional buildings. Loss of smart & climate responsive design with modernization of the building sector in developing countries especially.	Reviews examples of vernacular architecture & its building elements in Nepal & analyses in a qualitative manner which bioclimatic strategies applied	Trad. arch. in Nepal is adapted to the local climate conditions. Design optimized using natural resources: solar radi. & wind efficiently. techniques dont always meet modern living style
[19]	Tropical Monsoon, Tropical Savanna, Semi-arid	Analysis of internal comfort. Building effeciency in protecting from harsh climate	bioclimatic analysis & devel. based approach for arch. in NG. retrieves regional climatic data & characteristics from 36 meteorological stations	Research develops new bioclimaticchart, to prepare & prove the climate classification of Nigeria into 5 diff. regions as proper answer, dependent upon the vernacular NG. architecture
[20]	Warm Desert, Warm Semi-arid, Monsoon, Tropical Savanna	Analysis of Koppen study	Vegetation-based empirical climate classification system	Köppen-Geiger climate classification Led to proper classification of urban forms, building forms, materials, roof types, & architectural components for temperate-humid climate
[20]	Composite, Temperate, Hot-Dry, Warm-Humid Tropical	Analysis Atkinson Classification	Analysis of hot climates in relation to building needs using temperature, humidity, precipitation, sky conditions, solar radiation, & special conditions	Series of classification resolutions and applications to schemes, management of resource Led to proper classification of forms, materials, roof types, & arch. components for climate type
[21]	Tropical Monsoon, Savanna	Determine thermal comfort perception & conditions of naturally ventilation primary school buildings in a warm & humid environment, Imo State, Nigeria during the rainy & dry seasons from October 2017 to May 2018	Field study (7050) questionnaire investigates comfort temperature in two types of classrooms vernacular natural air & modern closed mechanical air.	Diff. in comfort perceptions attributed to diff. in the architectural characteristics of building categories. High temp. tolerance shown. AC's unnecessary energy consumption & carbon emission.
[22]	Various International regional	Energy efficiency & sustainability of traditional structures- in regards also to regionalism. Clarifies contents & issues raised in the studies on vernacular arch. & the knowledge & recommendations derived.	A database of research case-studies are refined, categorized & synthesized into a table of derivations to support diverse inquiries, & supportive resource	Increasing interest count & % of research objectives of vernacular architecture studies; Uneven geographic & climatic distribution of studies; shift tow. quantitative methods, generic findings
[23]	Warm Temperate, Mediterranean	Vernacular architecture as an essential part of cultural heritage, embodying design in harmony with nature, durability, & sustainability. The emergence of local design strategies as empirical rationality for comfortable environments	Case overview of the regional diff. in vernacular architecture in Portugal. It builds upon a major reference work: the National Survey on Regional Arch.	Vernaculars address social conflicts, global warming, & lack of harmony. Observed signs of renewed interest in rural space & vernacular revival
[24]	Various International Climates	Environmental design aspects of traditional architecture in a broad range of climatic conditions & building types.	Case-studies analyze appropriate technical & social solutions provided by vernacular & traditional architecture in detail.	Lessons directly from traditional & vernacular architecture & offers them as guidance & inspiration for new buildings

Table 1. Passive Vernacular Studies. A compilation of evaluations. References: [2, 15 – 24]

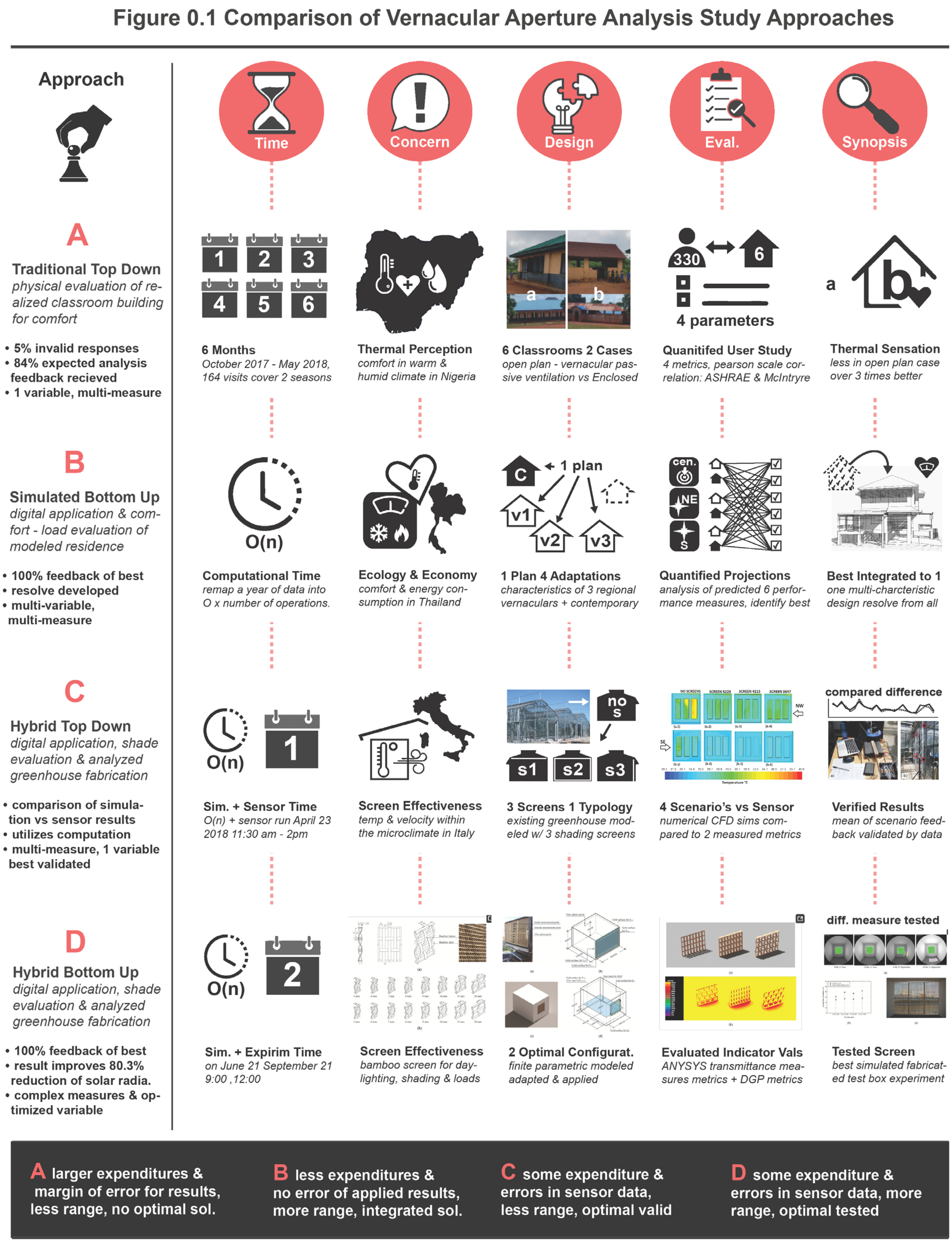


Figure 0.1. Comparison of Vernacular Aperture Analysis Study Approaches. References: A [25], B [26], C [27], D [28]

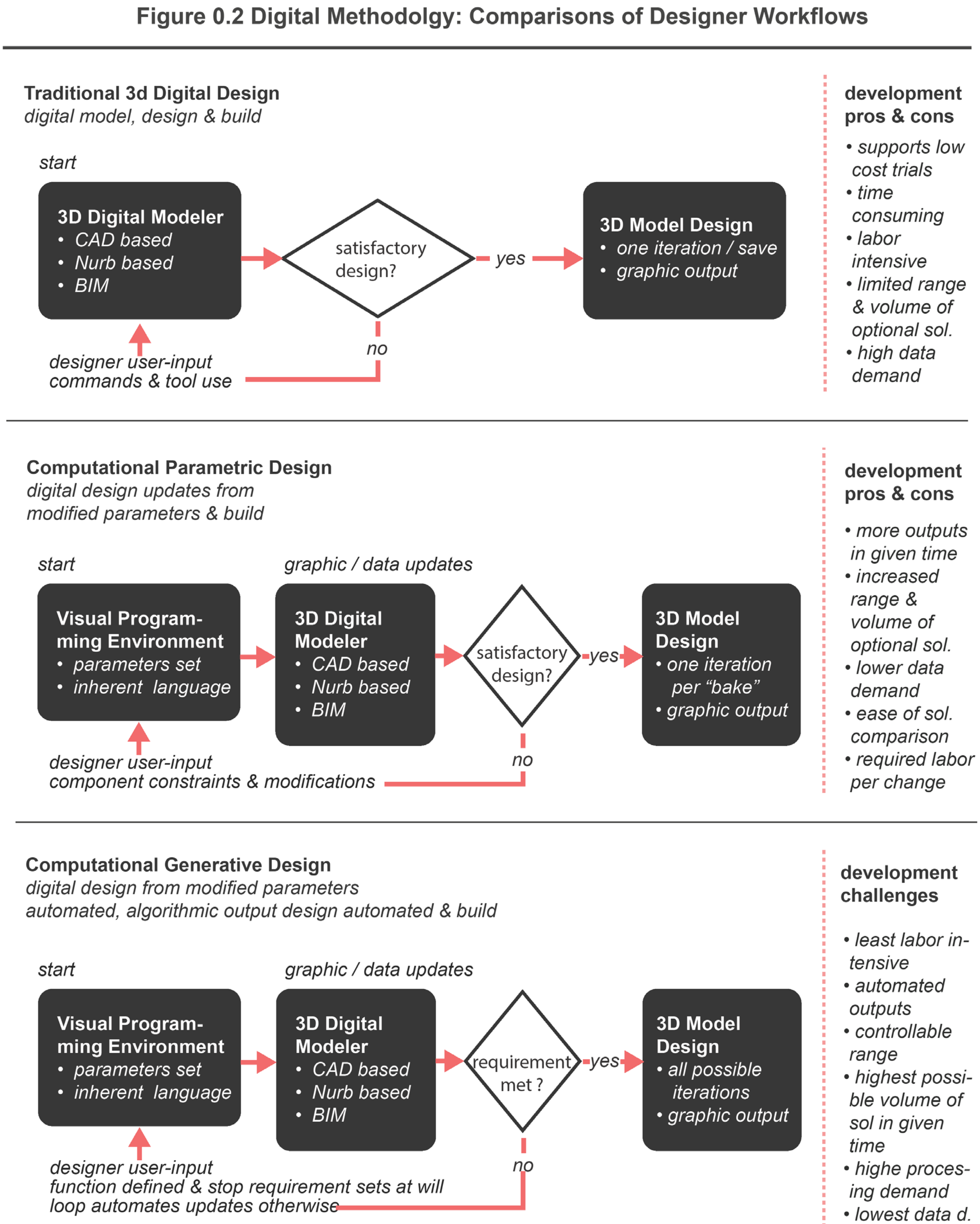


Figure 0.2. Digital Methodology: Comparisons of Designer Workflows

Figure 0.3 Parametric Design

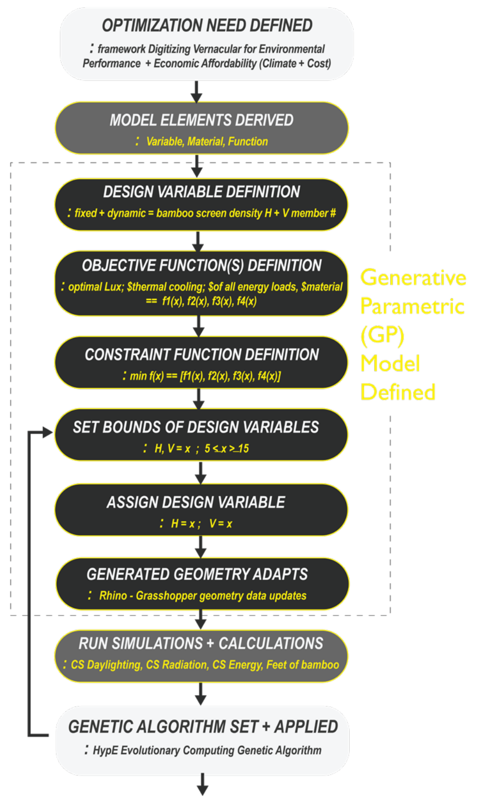


Figure 0.4 Design Optimization Flow

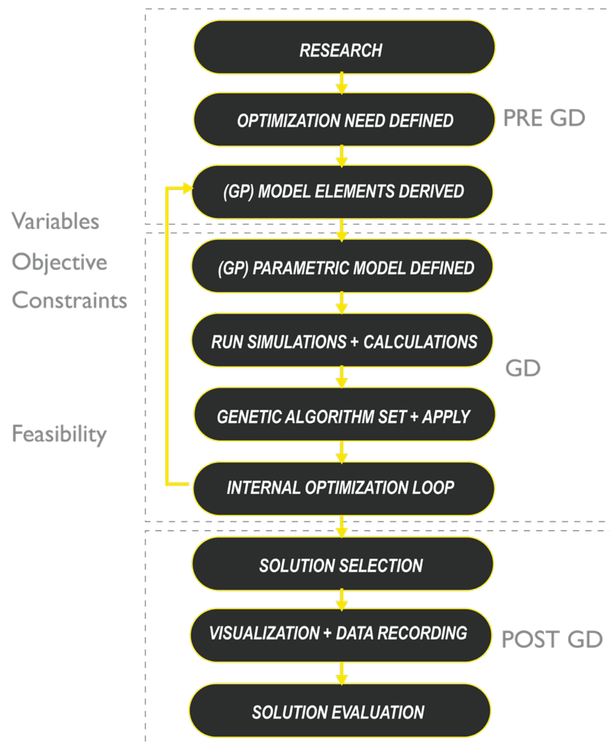


Figure 0.5 Generative Design Process

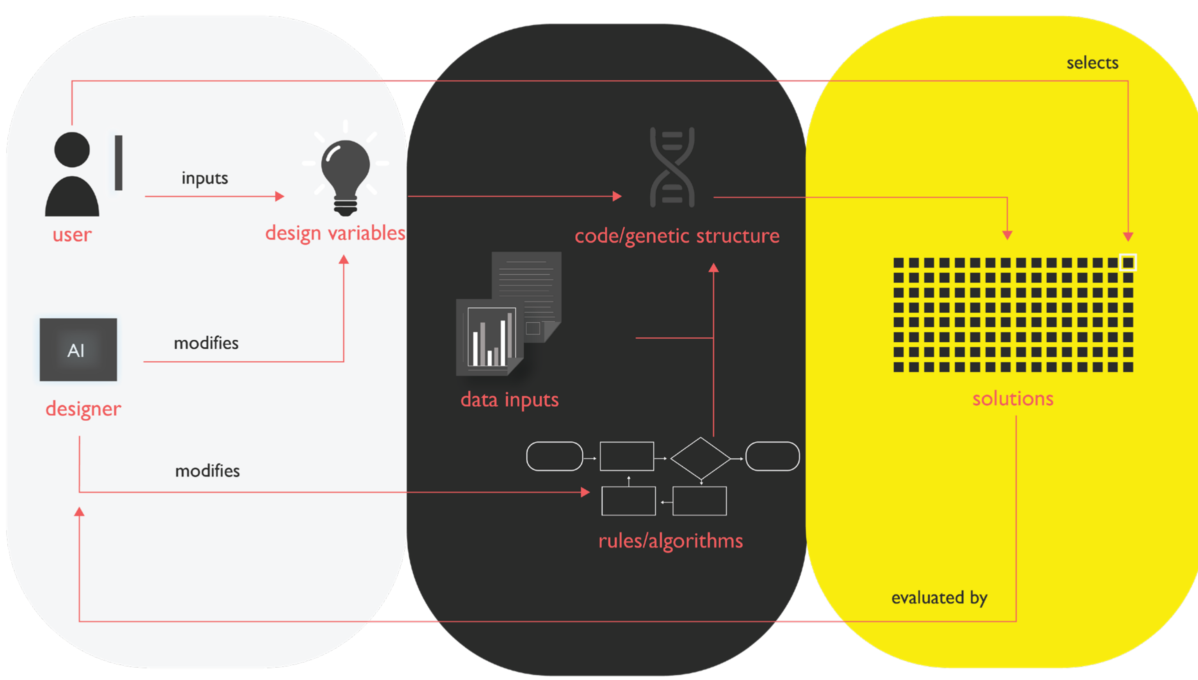


Figure 0.3. Parametric Design; Figure 0.4 Design Optimization; Figure 0.5 Generative Design Process

Figure 0.6 Evolutionary Computing Genetic Algorithms Overview

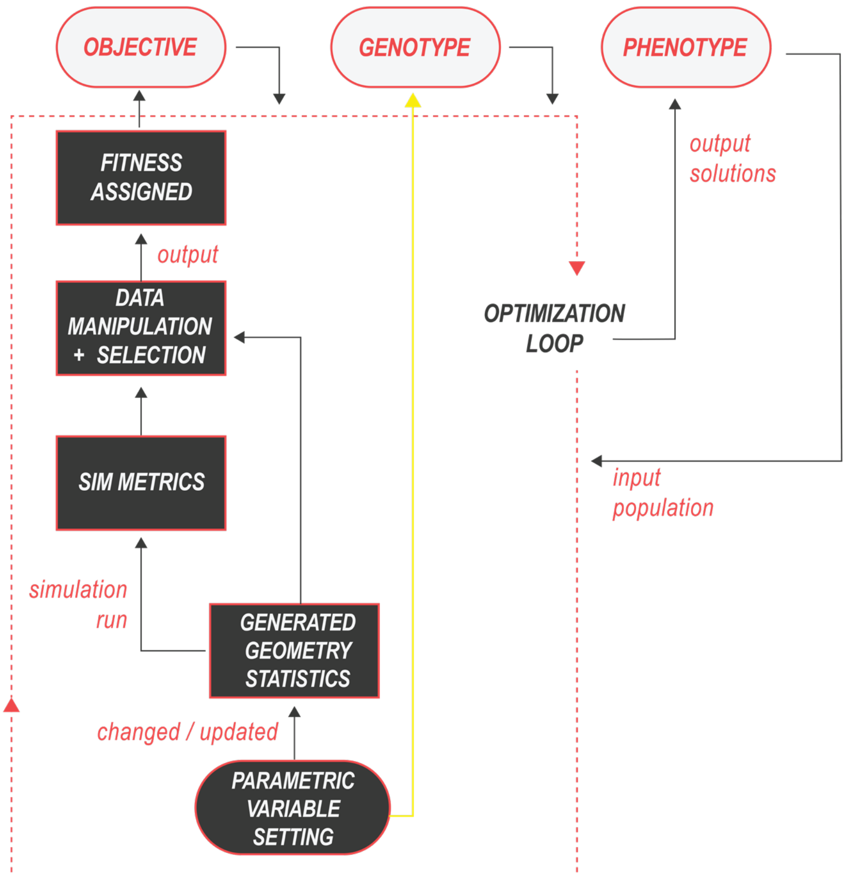


Figure 0.6. Evolutionary Computing Genetic Algorithms Overview: Objective, Genotype, Phenotype.

Figure 0.7 Evolutionary Computing Biological Evolution Mechanisms

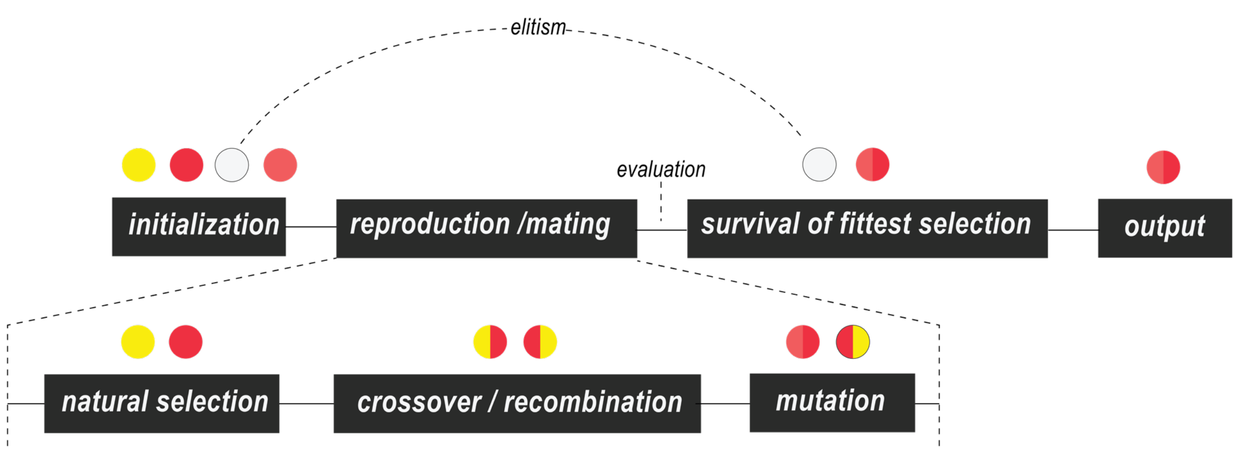


Figure 0.7 Evolutionary Computing Biological Evolution Mechanisms

CHAPTER 2: BACKGROUND

2.1 CLIMATE AND ECONOMY

In the 21st century, climate challenges are prevalent throughout the globe, often cooperating with unfavorable economic conditions to form complex problems in various communities. The climate change phenomenon attacks local, regional, and national goals for socio-economic policy addressing equity, sustainable development, growth, and prosperity [5]. A synthesized report on the *Economics of Adaptation to Climate Change* by the World Bank explains that globally, there is a $70 billion to $100 billion average climate adaptation cost per year projected between 2010 and 2050. This cost of the adaptation for a 2°C global increase in temperature is calculated at 2005 prices which does not account for inflation (*Figure 1.0*). It is concluded that there is a price to pay for climate-responsive adaptation which is more significant for developing countries as it relates to their projected GDPs. However, it can be determined that the impacts of climate change without adaptation are much more costly. Since "climate change will always hide beneath weather variability", keeping infrastructure, construction, as well as other sectors up to date with current climate changes significantly mitigates the cost of adaptations for the future [29]. Environmental economic principles validate that economic conditions and environmental conditions have a bidirectional relationship of impact as agents of configuration in a community or region. This phenomenon is often studied via a method called Environmental Kuznet's (E-K) hypothesis which implies an inverted U-shaped relationship between incomes and some environmental degradation factor/result such as S02 emissions [7].

Figure 1.0 Spatial Pattern of Years Exceeding 2°C Warming

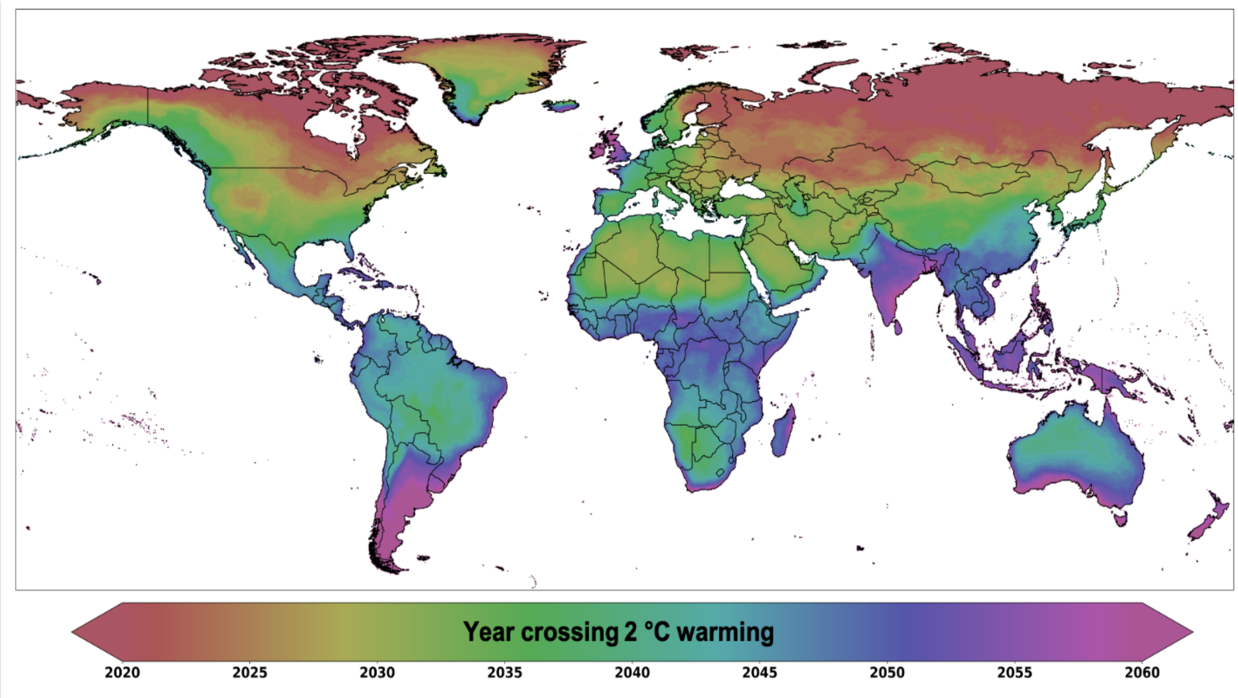
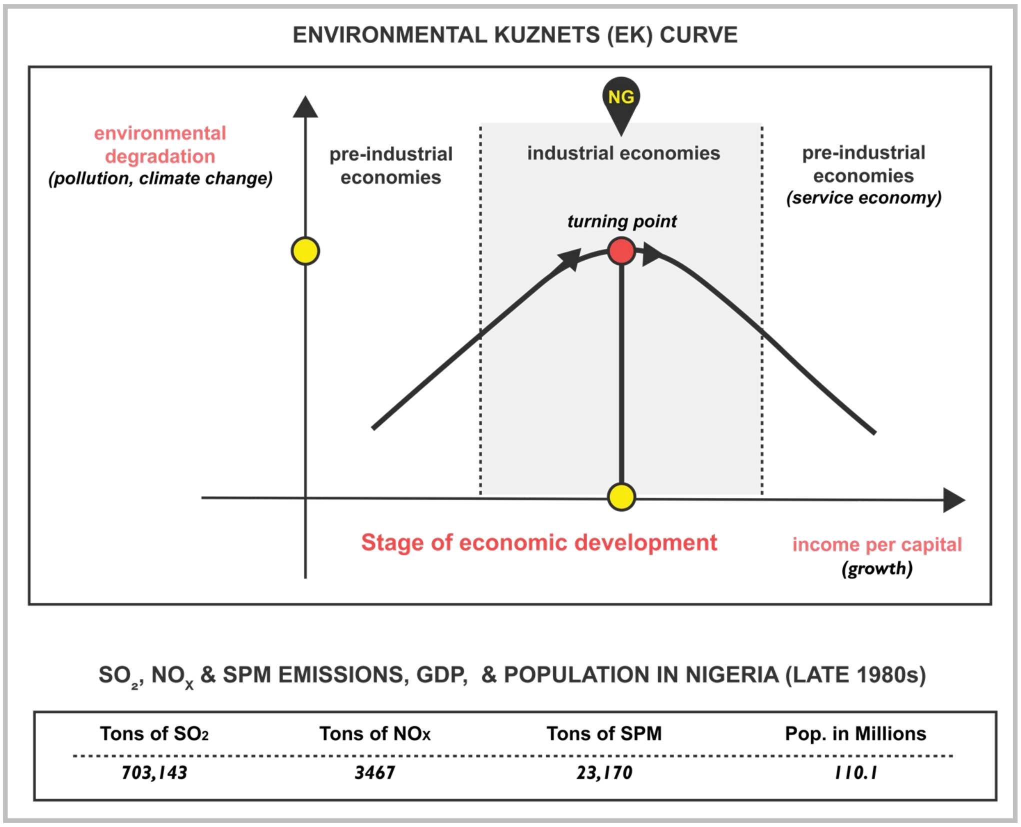


Figure 1.0. NASA's Global Daily Downscaled Projections: NEX-GDDP-CMIP6. "Spatial pattern of years exceeding the 2°C warming with respect to the baseline period (1950-1979). The 15-year moving average of the ensemble median of near-surface air temperature from 35 CMIP6 models (SSP585 scenario) was used in detecting years exceeding the 2°C warming."

The influences of climate change relevant to this thesis study include growing urbanization, extreme weather events, increased squatter settlements, degradation of coastal ecosystems, and rapidly developing infrastructure [73]. While these negative impacts threaten all countries, they are more severely sustained by poorer countries and their people due to vulnerabilities related to their limited capacity to bear climate variabilities and extremes. The bi-directional correlation between the increased contribution to/ impact of climate control and the IPC of a nation likely affects other economic metrics related to well-being and shelter. This inverted correlation indicated in *Figure 1.1* and *Figure 1.2* is subject to factors such as a nation's sectoral categorization as an industrial country. This relates to economic activity, size, and sectoral structure of the economy as well as the vintage of technology, environmental amenity demands, and lastly, conservation and environmental expenditures and their effectiveness [61][72]. Another factor of impact and emphasis in addition to the socio-economic condition is investigated. Indepth comparisons done by the OECD between the likely regional impacts of climate change and the region's vulnerability and adaptive capacity reveal this to be specific ecological systems or climate zones within various continental nations (*Figure 1.3),* [3].



Tons of SO_2	Tons of NO_x	Tons of SPM	Pop. in Millions
703,143	3467	23,170	110.1

Figure 1.1. Environmental Kuznets (EK) Curve [7]

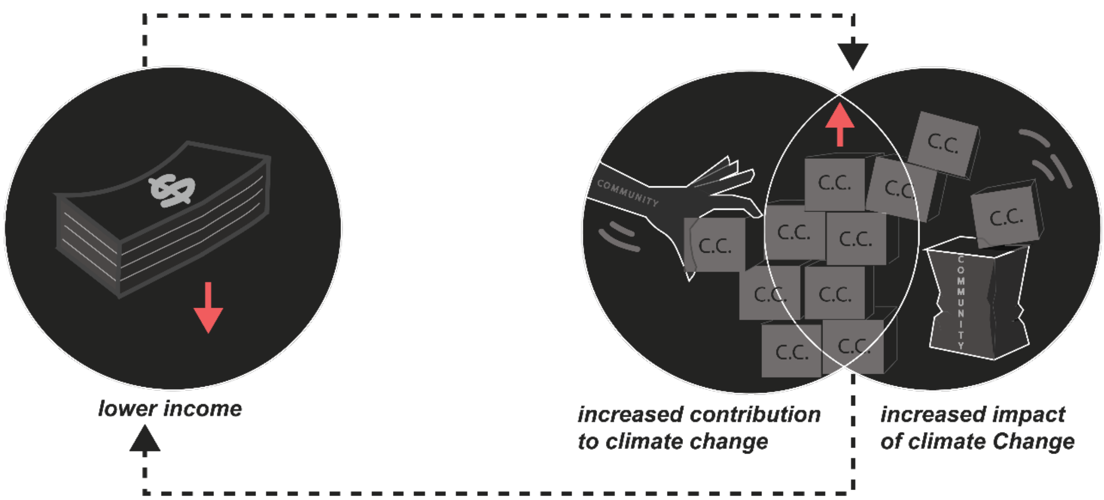


Figure 1.2. Income and Climate Change Loop

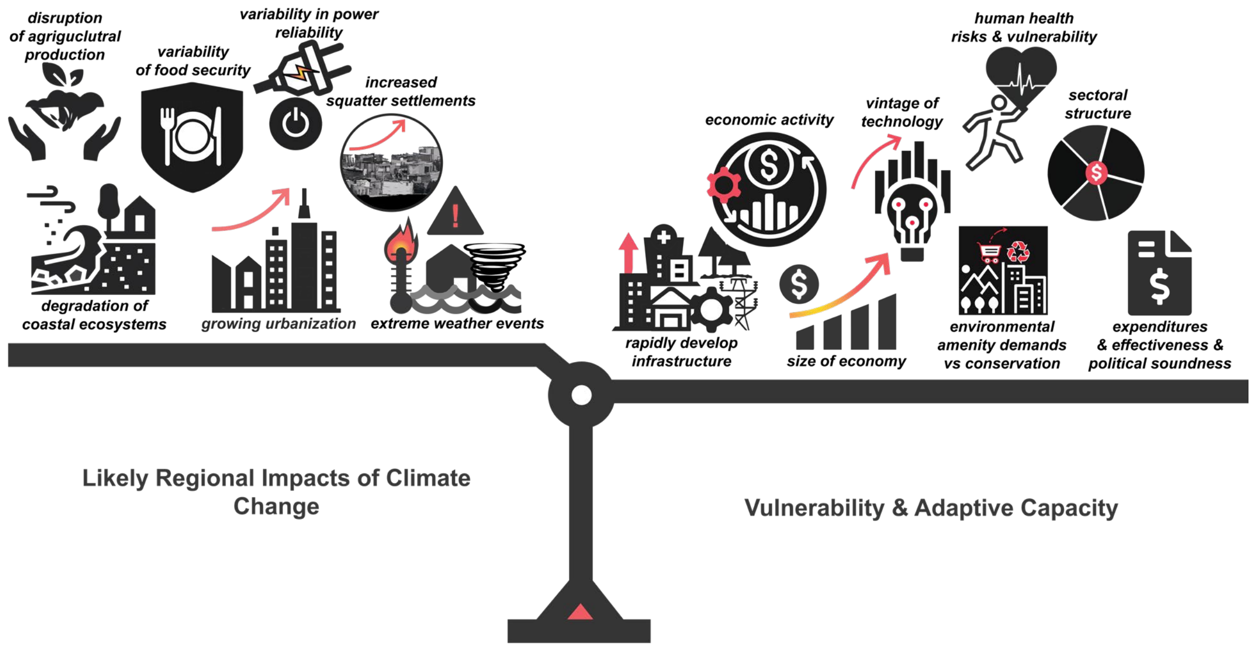


Figure 1.3. Regional Impacts, Vulnerability and Adaptive Capacity, info from [3, 8 – 11].

2.2 VERNACULAR VS CONTEMPORARY ARCHITECTURE

“Vernacular architecture is the result of hundreds of years of optimization to provide a comfortable shelter in a local climate using available materials and known construction technologies” [2, 30, 31, 32]. Vernacular architecture particularly reflects the traditions of the place of its existence. This means it adheres to the socioeconomic and environmental context which considers the historical conditions of the economy and climate (*Figure 4.5*). But it does not always adhere to updated governmental policy, standards, and regulations due to poor system application [33, 34]. In contrast, modern architecture may adhere to relatively current industry standards and universal styles propagating internationalism which lacks the equitable “harmony between the necessities of living, the environment, material resources and ideas on the use of space” particular to a locality or region (*Figure 4*), [35, 36, 37, 38]. This category of architecture tends to be more expensive in comparison to vernacular which instead, often utilizes naturally cultivated and locally manufactured building technology resources. It is common for strictly contemporary architecture to eradicate the rooted traditions of its context and particularly disregard climate response resulting even in the neglect of current sustainability standards and future goals [39, 40].

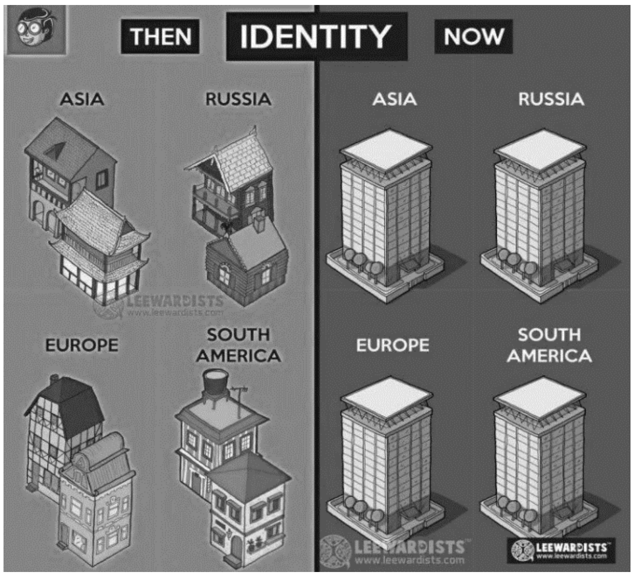


Figure 4. Displays the ambiguity of local identity. *Do all our cities look the same now?* [41]

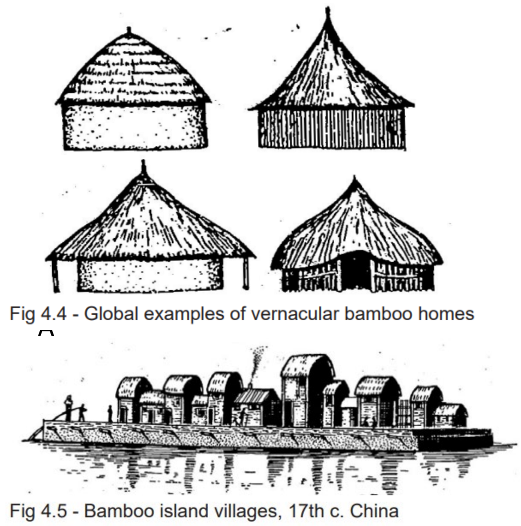


Figure 4.5. Historical Vernacular. derived from *Contemporary Bamboo Housing in South America* [42]

In his dissertation section, “A Bioclimatic Approach Redefining the Modern Vernacular” O’Connell looks at the work of architect and educator William McDonough. He finds that contemporary architecture suggests that even progressive solutions to a modern low-energy mandate can also lack a richer more holistic appreciation of the important relationships highlighted in section 1.1 of this thesis. McDonough’s observations of the “multitude of monolithic urban buildings with identical four-sided envelopes in complete denial of their vastly different climatic loads” conclude that the architecture of the late 20th century decades can be summed up to a “monument to the designer’s ignorance of where the sun is” [37]. It can be argued that the architecture of the 21st century also retains these same characteristics. A building system consists of the material used and the method of application also known as technology. The full benefit of vernacular integration is found in incorporating the full system; both material and means. A notable architect who utilized this was Severiano Mario Porto. He moved to the Amazon region in the

1970s and adopted local traditional methods. Porto adapted his buildings to the climate and site developing new construction methods making the use of local timber widely acceptable, creating a new hybrid typology. There are countless recent studies by the architectural community on the application of vernacular architecture to develop a resilient architecture that cooperates with climate although it was earlier approached as anthropological or archeological [43].

The emerging mediator between contemporary and vernacular is coined neo-vernacular architecture. It tends to incorporate acknowledgments of the current and future conditions of modern life into construction which fuses the best of both old practices and new technologies. Paul Oliver was suggesting this ideal when regarding the vernacular as a process of change and adaptation by people in specific situations and conditions that could involve modern building technology system components also [44]. This notion is investigated in “Lessons from Traditional Architecture: Design for a climatic responsive contemporary house in Thailand”. It concludes that the addition of bioclimatic vernacular elements and concepts to an improved design-build process better mitigates climate change in a new typology (*Figure 5* and *Figure 6*). This Digitizing Vernacular thesis also explores this notion to generate and digitally test an optimized vernacular building component that will significantly aid in addressing climate challenges specific to the place of application amongst other similar global communities.

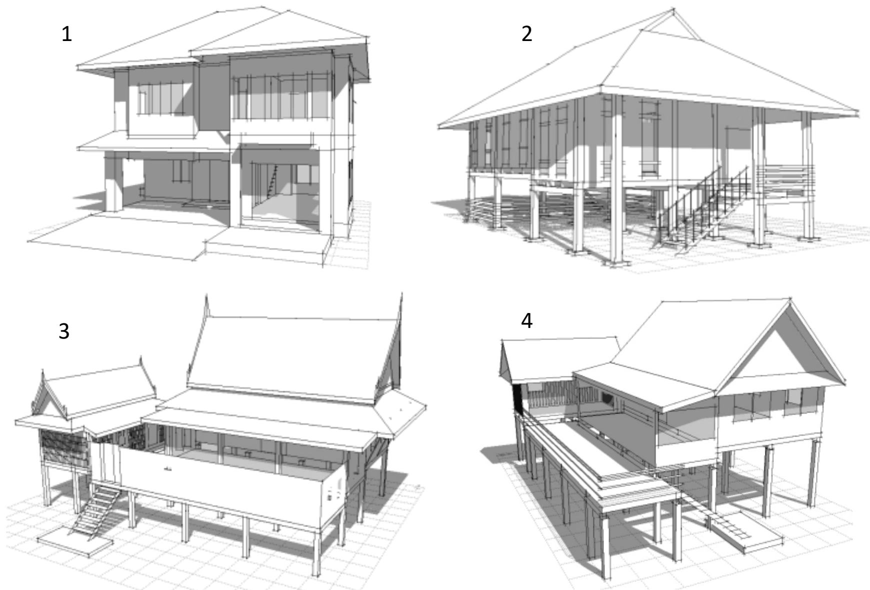


Figure 5. Lessons from Traditional Architecture: Design for a climatic responsive contemporary house in Thailand A. derived from - [26] Figure 1. Contemporary House in Thailand; [26] Figure 2. Traditional House, South region of Thailand; [26] Figure 4. Traditional House; Central region of Thailand; [26] Figure 5. Traditional House, North-east region of Thailand (2006)

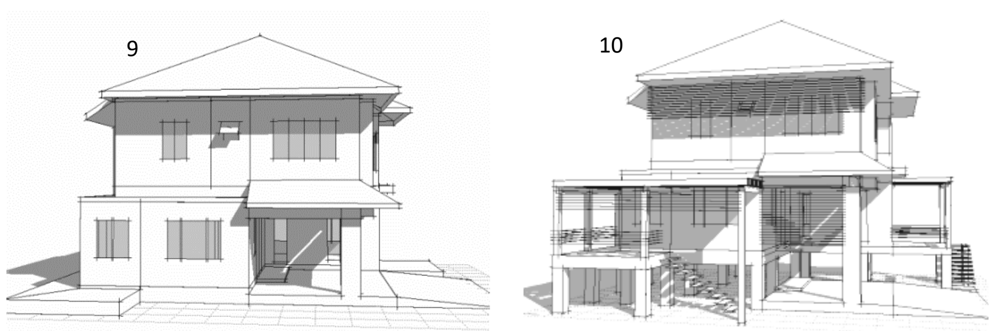


Figure 6. Lessons from Traditional Architecture: Design for a climatic responsive contemporary house in Thailand B. derived from - [26] Figure 9. Inadequate shading on west façade of a contemporary house in the central region at 3pm in June; [26] Figure 10. An improved contemporary design featuring additional shading, raised floors and shaded external platforms.

2.3 LAGOS, NIGERIA: URBAN SPRAWL, ECONOMY, AND CLIMATE

One of the most significant influences on all architecture but especially the vernacular, is the macro and micro-climates of the area in which the building is constructed. Understanding the location of focus is key in appropriating the correct building design systems that adhere to the geographic and socio-economic climate of the location. Nigeria is a country in sub-Saharan West Africa known to apply vernacular systems that are compatible with its extreme economic and atmospheric weather climate. For the sake of proving the thesis concept, the place of application is Lagos, Nigeria. The nation's economic and climate challenges form a complex as it relates to shelter and specifically housing. Nigeria falls into the 11% of nations that fall into all categories of stress from global urban sprawl according to a Mckinsey & Company study (*Figure 7*), [45]. Critical conditions are intertwined with the discussion of the housing crisis in global cities like Lagos.

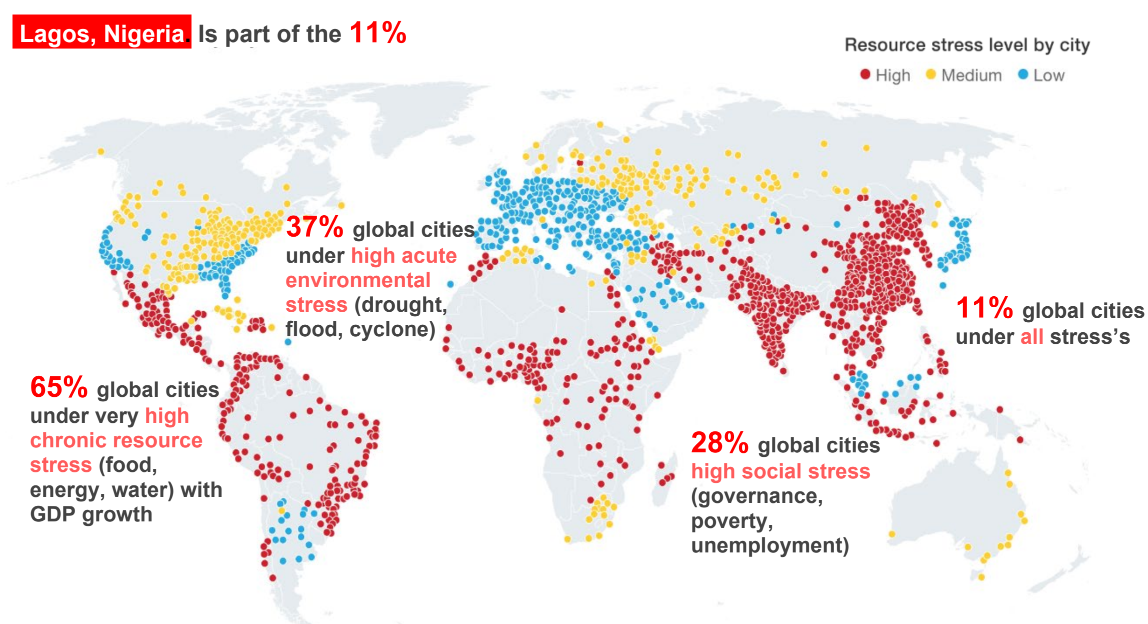


Figure 7. Internationalism Cultivating Global Urban Sprawl - Derived from Thriving Amid Turbulence: Imagining the Cities of the Future [45] (McKinsey and Company 2018).

According to UN-Habitat, around 33% of the urban population in the developing world in 2012, or about 863 million people, lived in slums. The proportion of the urban population living in slums was highest in Sub-Saharan Africa at 61.7% [29]. Nigeria is at the top of the ranks of that regional context with an estimated 60.1 to 70.0% of the 2005 urban population of 63,696,000 residing in these slums. That population has undoubtedly increased as the nation has grown between 2 to 3% each year since 1959 [46, 47,]. This is propagated by the fact that 40% or 83 million Nigerians are below the poverty line, while another 25% or 53 million are vulnerable [48, 49]. The UNCHS states that “There is no city in Nigeria, where the housing failure is more manifest than in Lagos” (*Figure 8*), [29]. According to Panayiotou, certain forms of environmental degradation including urban squatting and deteriorating urban slums, are related to the prevalence of underemployment especially in industrial nations [7, 50]. 33.30% unemployment as well as a 18.48% inflation rate and a $65 monthly minimum wage curate the economic condition of Nigeria (*Table.2*), [51, 52, 53, 54].

Table 2. Data of Nigerian Economy

	Poverty *below line*	Poverty *at risk*	Unemployment	Inflation Rate	Min. Wage *per month*	GDP *in billions*	Pop. Growth *% since 1959*	2022 Poverty *NBS Multi-Dim.*	2022 Poverty *WB projection*	Electricity Access *SouthSouth region*	Poverty *SouthSouth region*
Percentage *%*	40	25	33.3	18.48			2 - 3	63	42	82	53
Population *in Millions*	83	53						133	95	22.2	14.3
Price in USD *$*	< 1304.60				65	509.9				₦24 / $7	

Table.2 Data of Nigerian Economy, derived from [46, 48, 51-54]

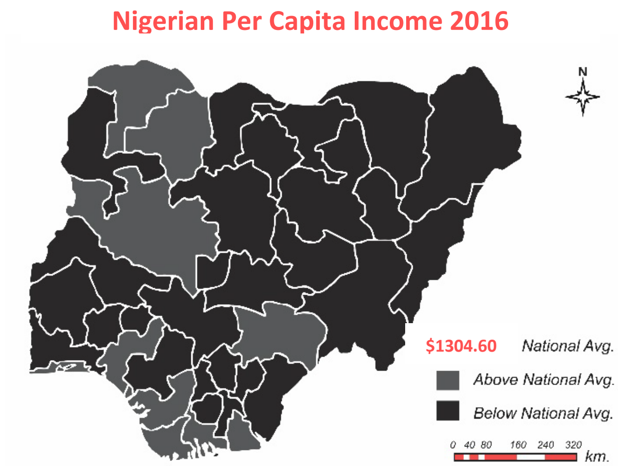


Figure 8. Nigerian Per Capita Income 2016 derived from [47]

In NG there is a prevalent battle for land and water among those investing in and developing modern architecture and those crafting vernacular architecture, principally where uncontrolled expansion occurs [34, 54, 55]. Slums are seen as a manifestation of the municipality's inability to keep up with urban sprawl (*Figure 7.5, 8.5*). In Lagos, there is twice as much transition of the land area into slums than are transition from slums. There are two times as much land used for slums as any other urban area. Half of the cleared vegetative land is used for this purpose, the second highest portion is undeveloped open space, which could then eventually be a target for more slum development [56, 57]. They are responses to urban degradation, poverty, crime, and unemployment in developing countries. Although highly perceived negatively, slums benefit the poor by providing affordable shelter particularly when the city government is unable to plan and provide affordable housing. This is the case in Lagos where unhousing and under-housing situations are expressed, and economic affordability is a major challenge. Vernacular architecture erected, and elements implemented in Nigerian squatter and slum communities have failed to adhere to changing governmental policies, stringent standards, and regulations. This is due to the extensive use of sub-standard materials causing rapid deterioration of houses & infrastructure that would aid growth and safety [58, 59, 60]. These informal communities are often found in conflict with government entities with numerous records of demolished communities and orders of destruction (*Figure 9*) [57, 59, 61, 62, 63, 64, 65, 66, 67]. A finding of the World Banks climate change, equity and vulnerability study was that one of the few soft mitigation methods of climate change that took precedent over hard measures in West Africa included upgrading urban slums and controlling the development of new ones [68]. This thesis provides a means of which upgrade squatter and slum constructions and develop new typologies of mutually beneficial uniform communities. This is a relevant resolve since 75% of the dwelling units in urban centers in Nigeria are substandard & are sited as slums [68, 69, 70].

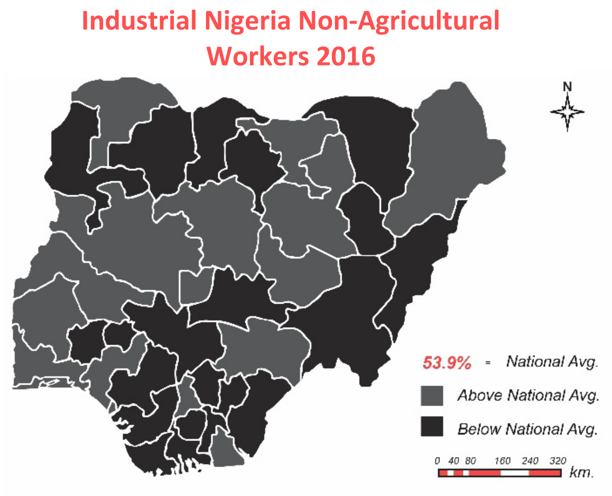


Figure 9.5. Nigerian Economy Non-Agricultural Workers 2016 derived from [48]

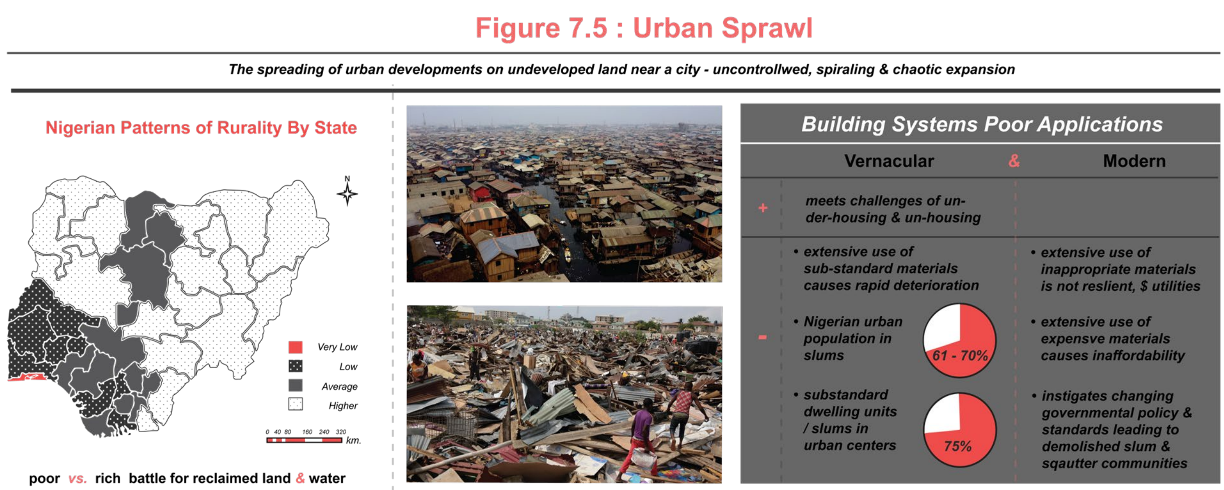


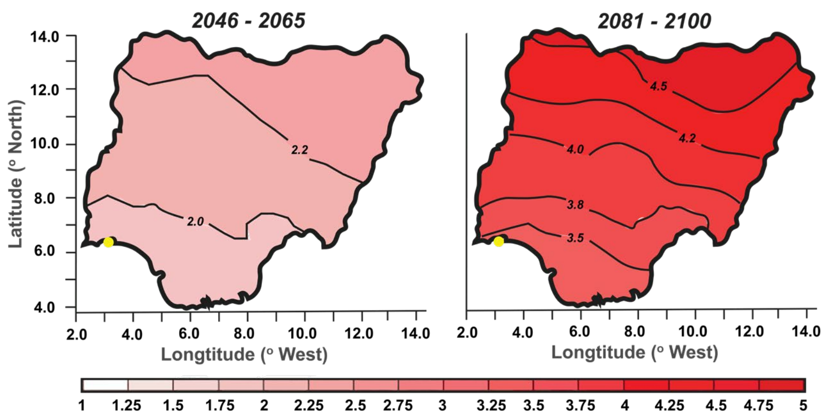
Figure 7.5 Nigerian Urban Sprawl Compilation [47, 55 -70]

Figure 8.5. Lagos Chaos From. [71]

Figure 9. Demolished Squatter Settlement Contrasts Modern Developments. From [72]

The categorization of Nigeria as a major industrial country in the West African sub-region and Africa south of the Sahara places the nation at the climax of the EK Curve [73]. This means that in occurrence are the highest levels of environmental degradation, which translates to climate impact and contribution (*Figure 1*, *Figure 2, Figure 9.5).* Nigeria is characterized by three distinct climate zones, a tropical monsoon climate in the south, a tropical savanna climate for most of the central regions, and a Sahelian hot and semi-arid climate in the north of the country (*Figure 10*). There are magnitude effects of climate change projected including a temperature increase of roughly 32 - 34 degrees Fahrenheit by 2020-2050 and 38 degrees by 2046 - 2065 according to a 2011 study by the BNRCC that was published by the World Bank [68, 73, 74]. It also brings extreme variations in rainfall. Another result is the hyper-frequency of typical disasters. Some targeted for vulnerability mitigation in this republic are floods, soil, and coastal erosion, landslides, tidal waves, coastal erosion, sandstorms, oil spillage, locust or insect infestations, and, increasing temperatures of extreme heat, a primary focus of remission by this thesis [75]. Takeaways from the findings of the conducted analysis "Climate responsive building design strategies of vernacular architecture in Nepal" include implemented climate-response design strategies applicable to subtropical zones (*Table 1, 3*). The adapted strategies including the reduction of direct solar heat gain confronted in this thesis' design problem solution. The enhancement of air movement and ventilation is not explicitly adopted as an objective but is inherently applied. Other aspects regarding mass, orientations, and roofing happen to be incorporated into the derivation of a base geometric model utilized in this vernacular optimization study [76, 77, 78, 79, 80, 81]

A - Heat Increase

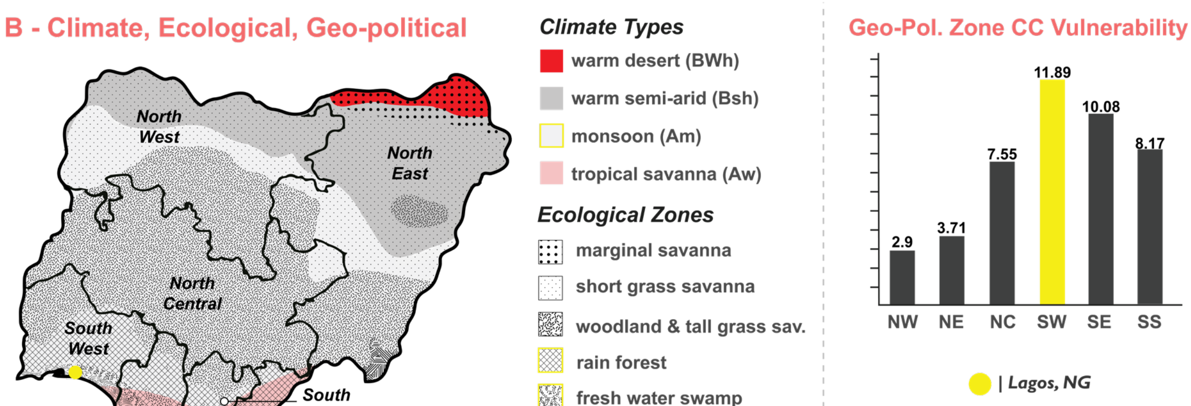


Daily Temp.	degrees in celsius	degrees in fahrenheit
Mean Current	33.1°	91.5°
Projected Increase	1.59° - 2.72°	34.86° - 36.90°

= Lagos, NG

Figure 10 – A. Nigerian Climate Conditions Compiled: Heat Increase. Derived from: [68, 74, 75].

B - Climate, Ecological, Geo-political



Projected Trends of Climate Variables

Ex. Heat : 2046-'65 : 95°-100°f

eco-zone	temp.	extreme heat days	rainfall amnt.	rainfall variab.	droughts	storms & floods	sea lev. rise
w&tg s	↑	167.4	↓	↑	↑	likely	
sg s	↑	245.8	↓	↑	↑	likely	
mg	↑	109	↑	↑	likely	↑	↑
rf	↑	128.6	↑	↑	likely	↑	

Figure 10 – B. Nigerian Climate Conditions Compiled: Climate, Ecological, Geo-political. Derived from: [68, 74, 75, 82, 83].

Table 3. Vernacular Climatic Responsive Analysis

Climate-Responsive Design Strategy	Subtropical Zone
high thermal mass of walls & floors	
hight thermal mass with night ventilation	○
building orientation north - south	◒
compact settlement & building layout	
low thermal mass of walls & floors	●
light well insulated roof	●
reduction of direct solar heat gain in summer	●
enhancement of air movement in summer	●
protection from heavy rain	●
outdoor sleeping space for summer	●
medium sized openings	◒
shading of openings in summer	

applied ● partial ◒ not applied ○ not analyzed

Table 3. Vernacular Climatic Responsive Analysis. From Table 8 Climate-Responsive Design Strategies in Vernacular Architecture of Different Climatic Zones of Nepal [2]

The translation of climate concerns as it applies to building systems in Nigeria typically places an emphasis on strength; tensile & compressive, daylighting, ventilation, and passive cooling. Some Vernacular systems in Nigeria include systems utilizing woven cleft wood, split bamboo, creepers, bamboo palm fronds, palm fronds, palms, woven mats, and grass with local woods or stones. Mud or dung, a mixture of powdered vegetation is used as reinforcements along with stones at times, and sand-casting. methods/technologies: mud, bamboo, stone, grasses, leaves, reeds, cow dung (*Figure 11)*. The vernacular element developed through computational means chosen for application here in Nigeria in the proof of concept is light filtering screens that can be configured to respond to climate and economic conditions. Specifically, a bamboo screen system is chosen as it is prevalent in (sub)tropical Nigeria but is also found in many nations around the world (*Figure 12*). Bamboo is widely used throughout the nation's south and can be found naturally or salvaged from closing construction sites where it is used as scaffolding (*Figure 15*)[84]. There are roughly 18 million square miles of land suitable for its growth in Nigeria [85, 86]. Some targeted areas of concern for the design problem include comfort and function, daylighting, and internal radiation, as well as mechanical and electrical load costs and material costs to address the economic concerns in Lagos [78, 79, 87, 88, 89].

Nigerian Vernacular Systems

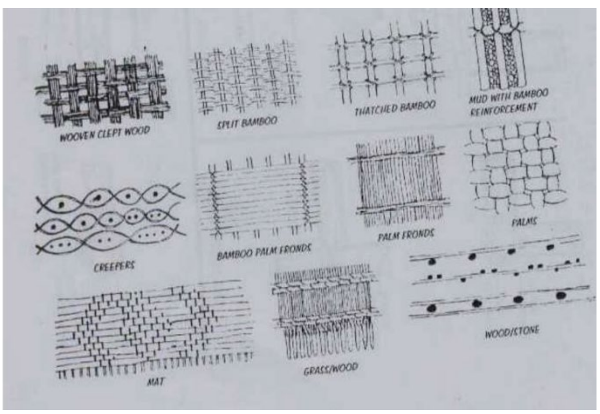


Figure 11 Nigerian Vernacular Systems. Common materials used in the construction of African Traditional Buildings [38]

Nigerian Bamboo Prevalence

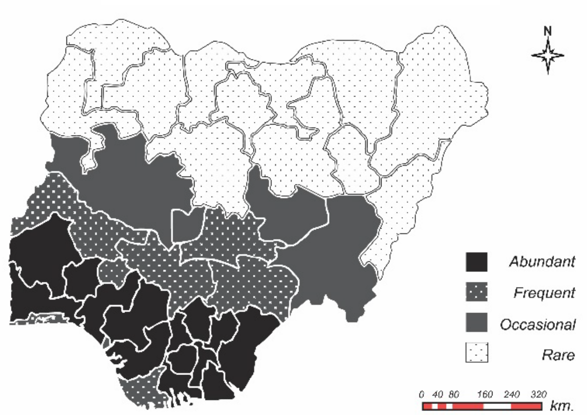


Figure 12 Nigeria's Bamboo Prevalence. From Source & Availability [85]

The use of Bamboo amongst other traditional system components have been vetted over hundreds of years of application and analysis. "The knowledge derived from vernacular architecture is at the core of a truly sustainable design" [63, 67, 90, 91, 92]. Vernacular architecture has been found feasible for climate-responsive construction practices in Nigeria (*Figure 13,14*). Reference can be made to several Nigerian and other global precedent studies that have proven that better thermal performance can be achieved by passive measures in vernacular architecture, some of which are earlier cited (*Table 1*).

Figure 13. 48-hour ‘bamboo bungalow’ plan launched to tackle housing shortage in Nigeria [93].

Figure 14. The Dominican Institute’s lounge and refectory feature stone, bamboo screens, brick and sand-casted screen walls. The latter provide both natural ventilation and large-scale decoration [94].

Figure 15. Nigerian Bamboo Scaffolding 12/2020

Figure 16. Nigerian Vernaculars 12/2020

CHAPTER 3: METHODOLOGY

3.1 OVERVIEW

This project is implemented with mixed methods to achieve two goals [95, 96, 97]. The first goal is to develop a scalable framework that can be adapted for future use in solving design problems with the same desired output and inputs as the proof-of-concept (POC) study. Specifically, a grasshopper simplified script is a tool used for the achievement of the second goal; to produce the desired output of a set of configured bamboo shading screen designs of user-specified type, optimal for environmental performance and cost efficiency (*Figure 17*). The design solution: drawings and specifications, should be suitable for the fabrication and application of the screens on user-specified apertures of a building in a user-specified location. Ideally, for best results a context with a tropical or subtropical climate like the POC study southern Nigerian region should be selected (*Figure 18).* The framework's computational script consists of 4 portions. 1st the geometric model is developed using Rhinoceros as a viewport for the visual programmer grasshopper where the reflected model geometries are configured with adapted parameters. 2nd the simulations and calculations are done to obtain goal values and model values. The climate studio plug-in is used to set up several environmental simulations from within the programming environment and its outputs feed into part 3. The 3rd portion is the optimization engine which in this case is the tool *Octopus* [98, 99]. The final portion part 4 enables the graphic visualization and data recording of the optimization outputs allowing for the capture of the resolved designs drawings and specifications for further implementation in the design process *(Figure 19).*

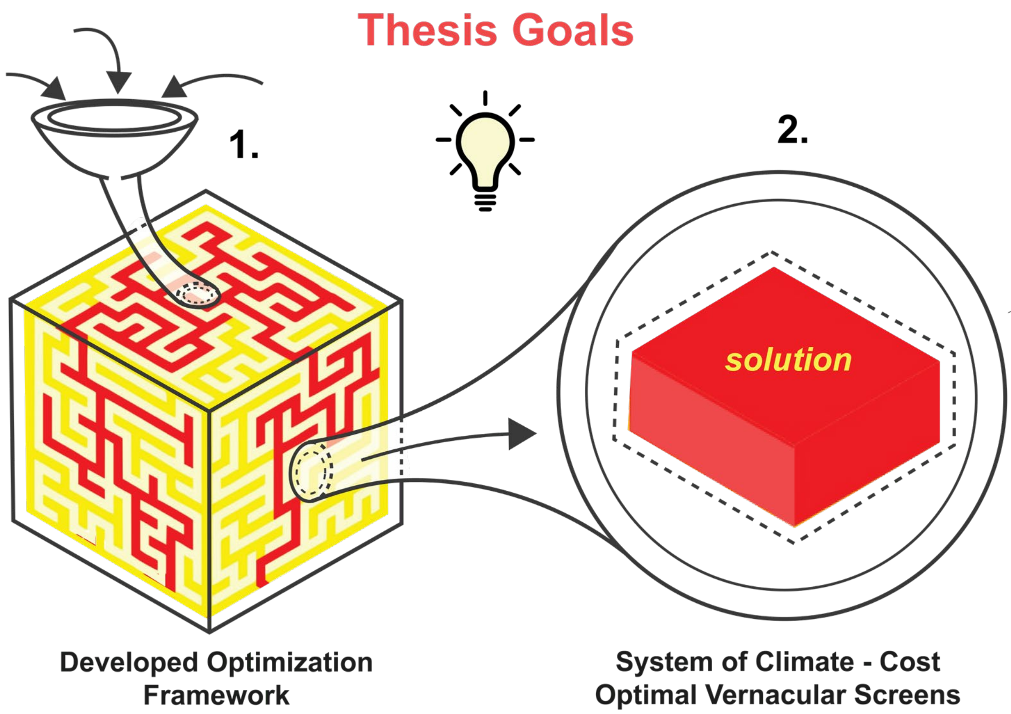


Figure 17. Digitizing Nigerian Vernacular Bamboo Screen Thesis Goals

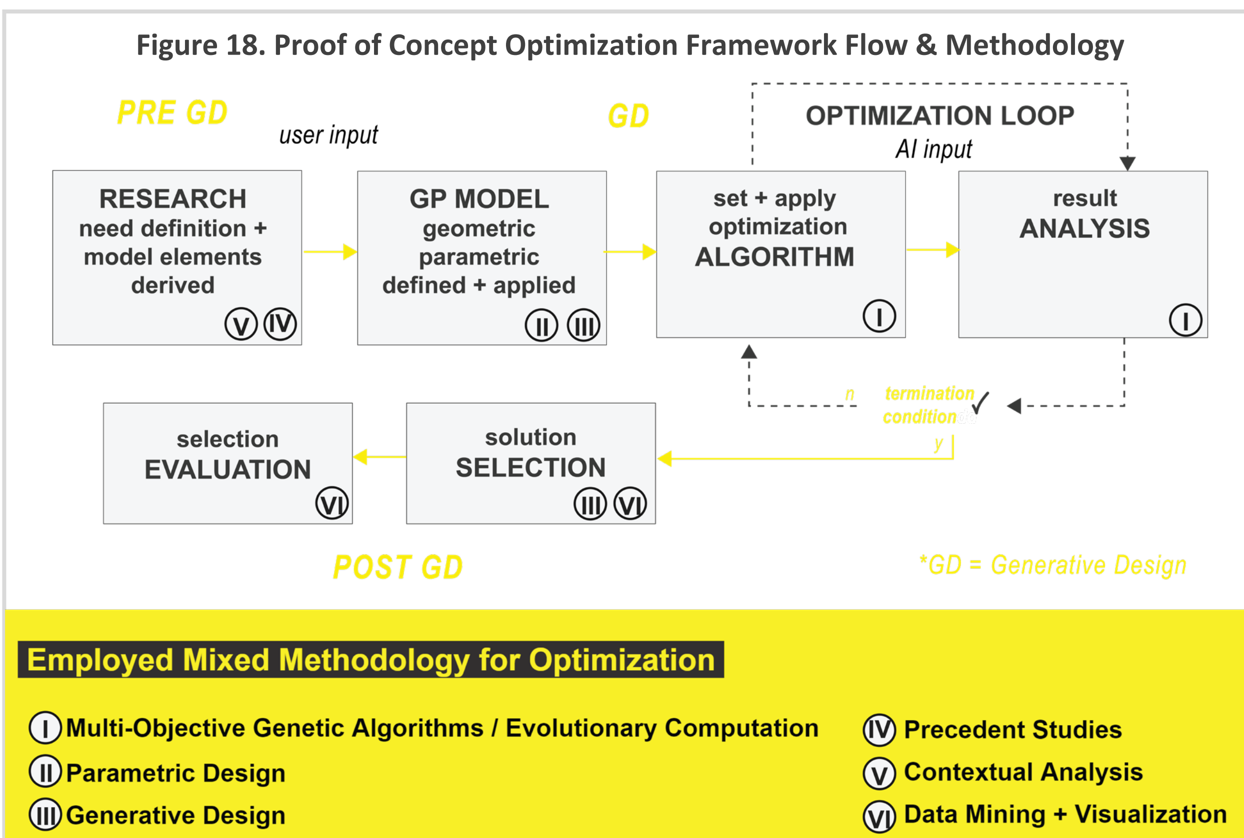


Figure 18. Proof of Concept Optimization Framework Flow & Methodology [100]

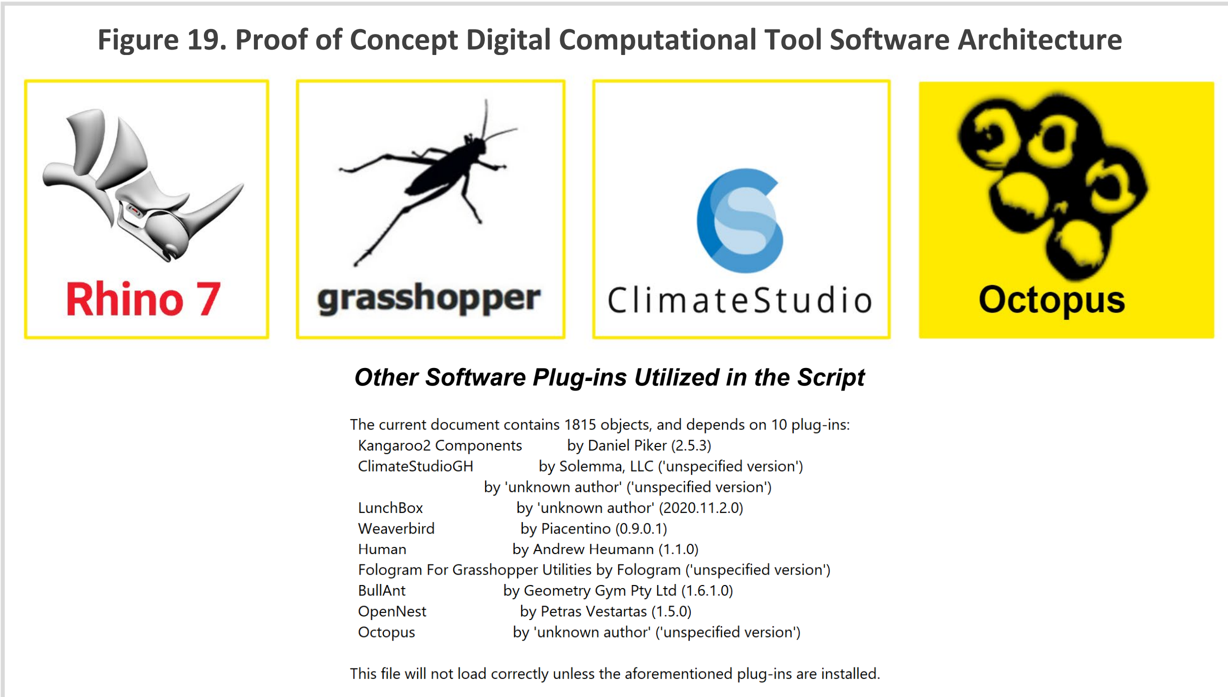
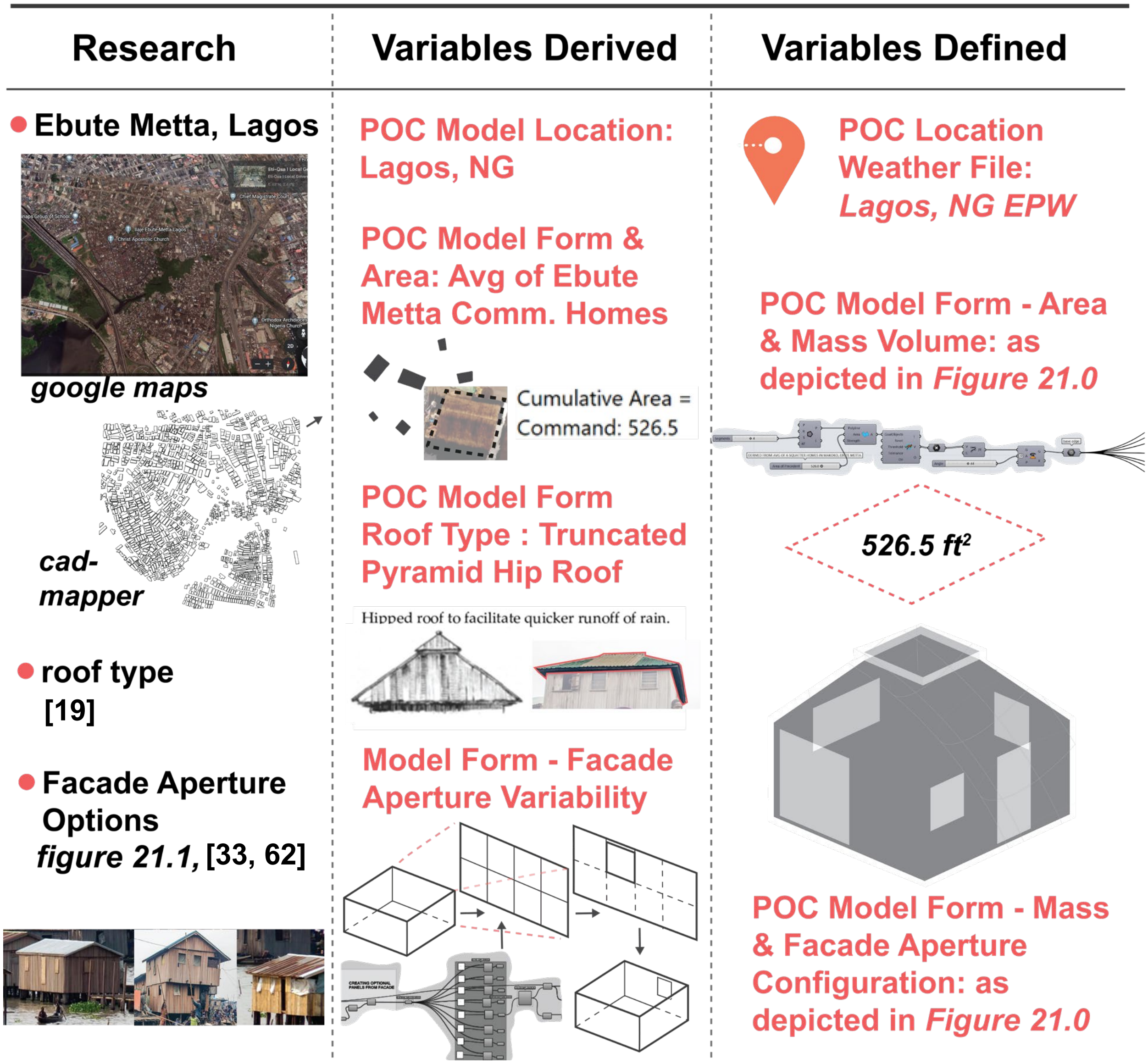


Figure 19 Proof of Concept Digital Computational Tool Software Architecture

3.2 PROOF OF CONCEPT MODEL

The optimization process defines the (GP) geometric parametric base model necessary to eventually set up the solution space of the optimization engine [100, 101]. This model is developed with version 7 of *Rhinoceros,* a 3d computer graphics nurbs-based CAD modeling software application created by Robert McNeel & Associates. It also consists of the natively integrated visual programming language and environment *Grasshopper.* The plug-in` developed by McNeel's David Rutten is what gives the GP model the capability to parametrically manipulate geometric data. This portion of the model consists of geometry and visual programming components that output the graphics and data of the base building's complete geometric volume. For advanced opportunities of visual production and specifications, the entire GP script run in the two integrated programs can also be run from the architectural industry's building information modeling software Autodesk's Revit via a plug-in called *Rhino Inside*.

Figure 20. POC - GP Model Variable - Parameter Derivation & Definition



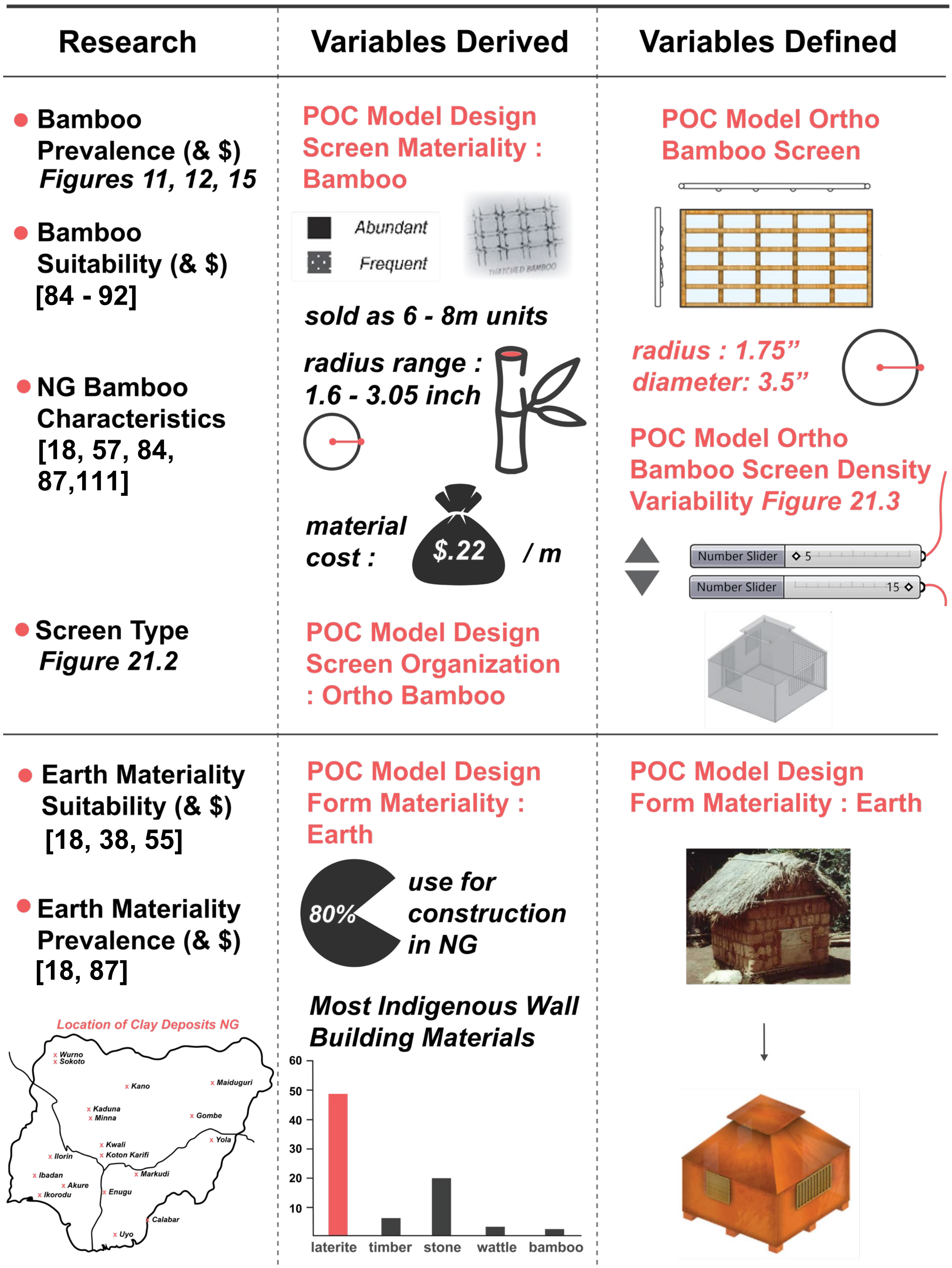


Figure 20. (POC) Proof of Concept (GP) Geometric Parametric Model Variable - Parameter Derivation & Definition

3.3 PORTION 1: GEOMETRIC PARAMETRIC MODEL DEVELOPMENT

The values used to set the variables which create the POC study's GP geometry are first derived from the background research, context analysis, and goals of the project. The determination was to address the housing crisis in Lagos, Nigeria, particularly the low-income waterside community of Ebute Metta. The rectilinear floor plate shape, the square footage as a median of a sample of the community's vernacular homes, and even the truncated pyramid hip roof style is selected in this manner. In this case the fixed apertures of the four facades were parametrically selected from the divisions on each face, based on existing opening configurations used in Lagos squatter communities (see image of the squatter on river overview). However, for the external user of the framework, the façade portions can be selected, defining the set location and arrangement of doors and/or windows as an initial model input. This along with variables of the volume form and EPW location file input *(Figure 20, 21.0, 21.1)***.** The location and dimensions of the apertures for the building are the model data that is implemented for use in applying the selected screen type. This basic setup and variable constraints of the geometries of representational bamboo shoots are fixed. The decision to apply shading screens as the subject study: vernacular building component, comes from the extreme heat climate change threat in Lagos. First, a screen-type pre-study inspired by [28], was conducted to implement the best-case climate-responsive, comfort-improving option to utilize in the POC, the orthogonal option was the resolve *(Figure 21.2, Table 4).* This is then applied to the apertures utilizing the geometric data of the outline curve lengths griding the negative space. The geometry is appropriately adjusted in the script to meet properly to eventually form a cohesive screen. Applied is the fixed material radius of the bamboo derived from the context research was another user input for the general application of this framework (*Figure 20, 21.3*). The solely calculated raw value of material cost is taken from the model's parametric geometry output of the configured screens, this is calculated by the total length of bamboo used in feet as multiplied by the unit cost as sold in location for the total cost of each screen and the entire screen system. This value will be minimized so that the produced vernacular solution is as affordable as possible *(Figure 21.4).*

Figure 21.0 POC - GP Model Final Geometry & Façade Apertures

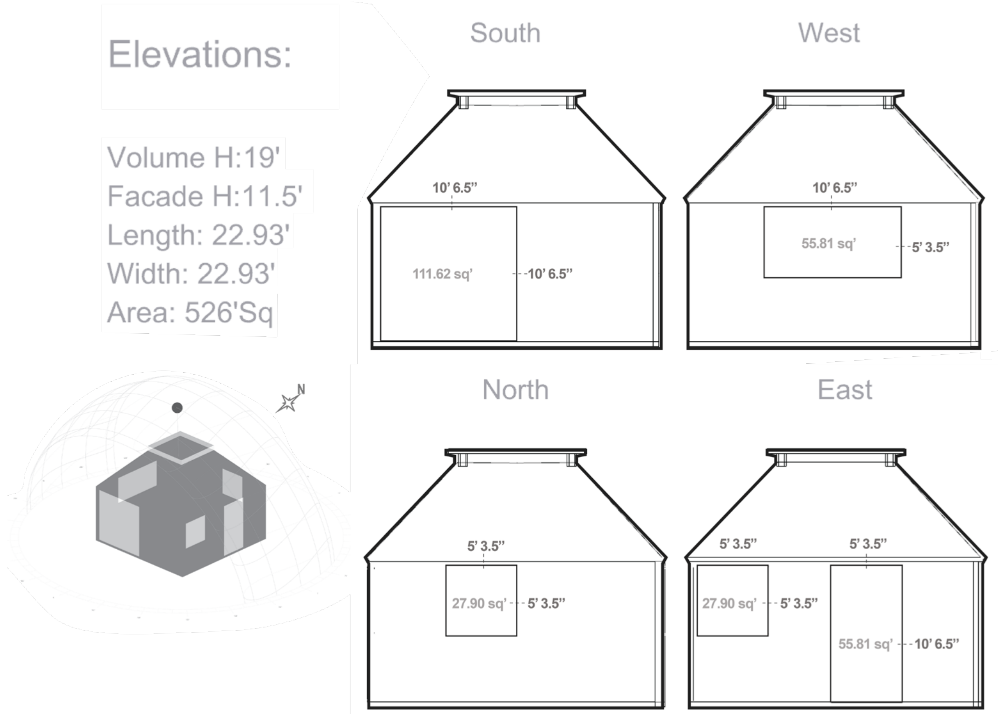


Figure 21.0 (POC) Proof of Concept (GP) Geometric Parametric Model Final Geometry & Façade

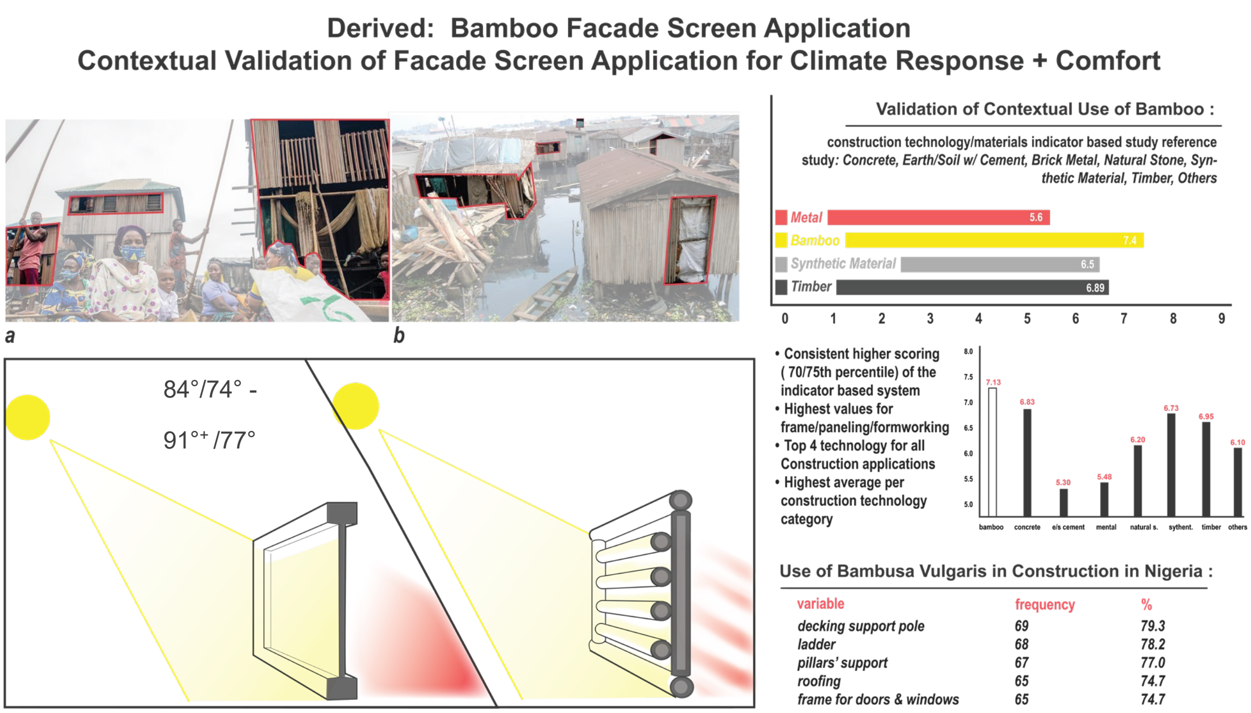
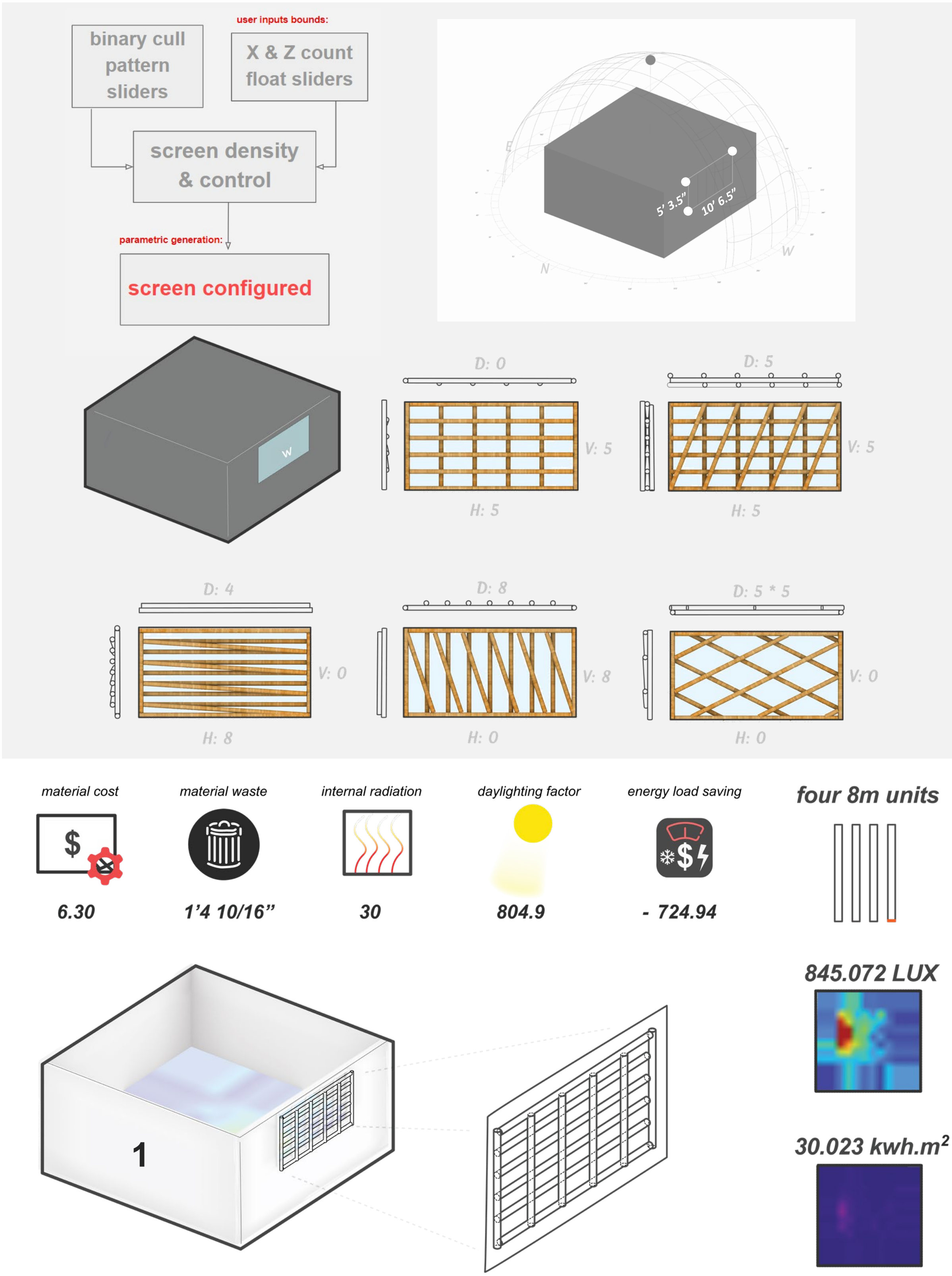
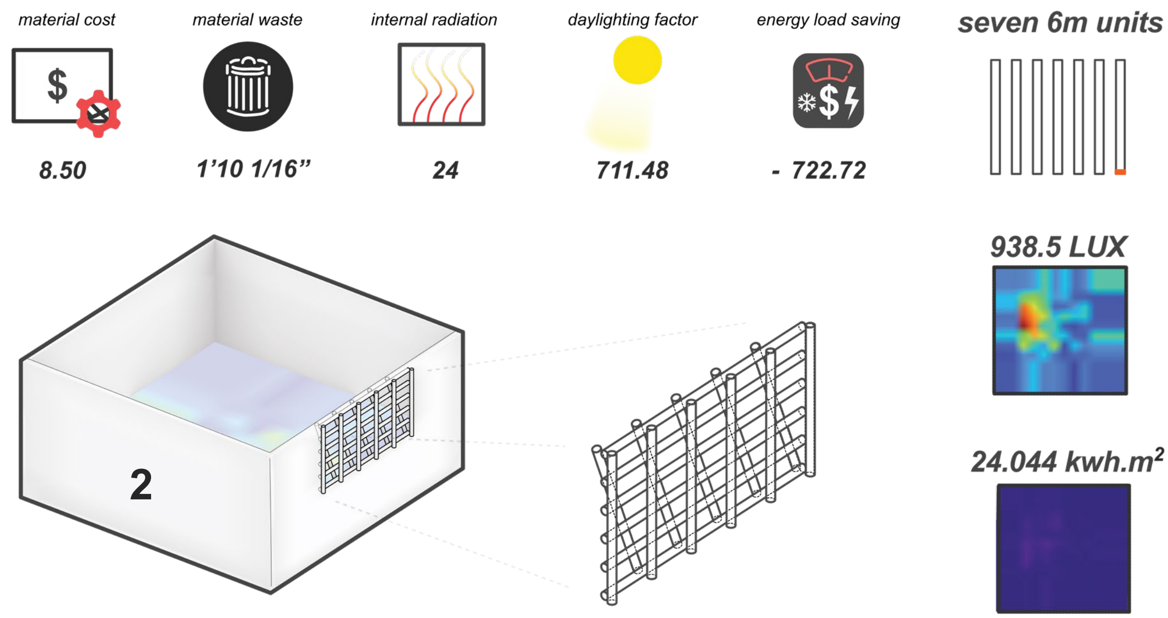
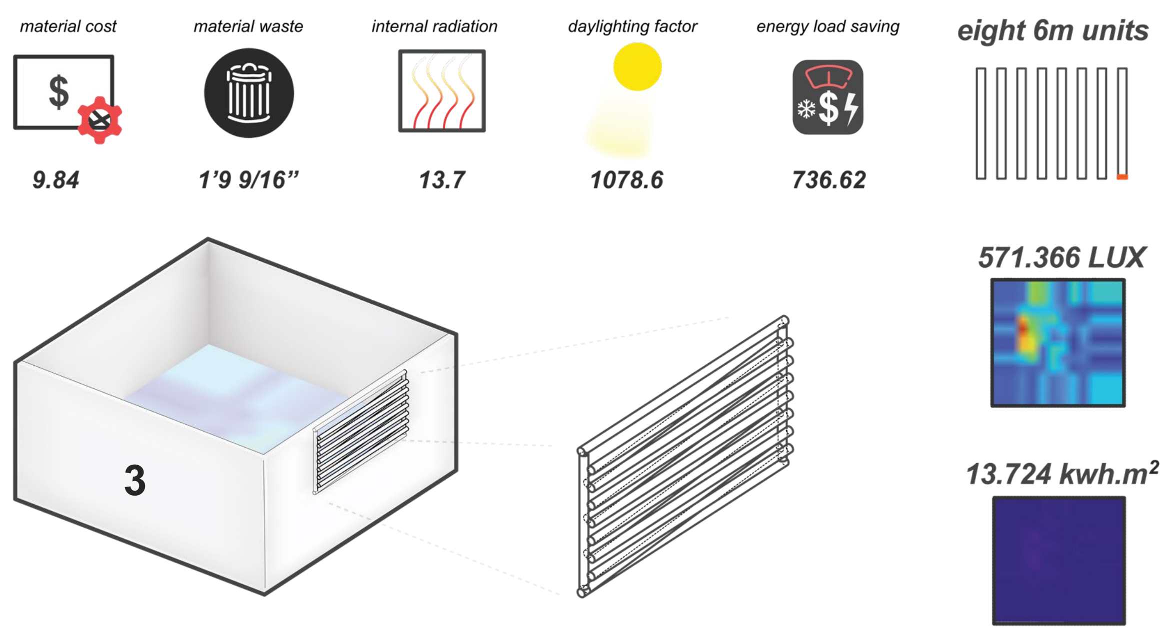


Figure 21.1 POC - GP Model Variable Screen Component Derivation [43], (a & b Ref [58], Ref [72, 57].

Figure 21.2 Pre-Study for GP Model Variable: POC Screen Type & Configuration




material cost
material waste
internal radiation
daylighting factor
energy load saving
seven 6m units
8.50
1’10 1/16”
24
711.48
- 722.72
938.5 LUX
2
24.044 kwh.m2


material cost
material waste
internal radiation
daylighting factor
energy load saving
eight 6m units
9.84
1’9 9/16”
13.7
1078.6
736.62
571.366 LUX
3
13.724 kwh.m2

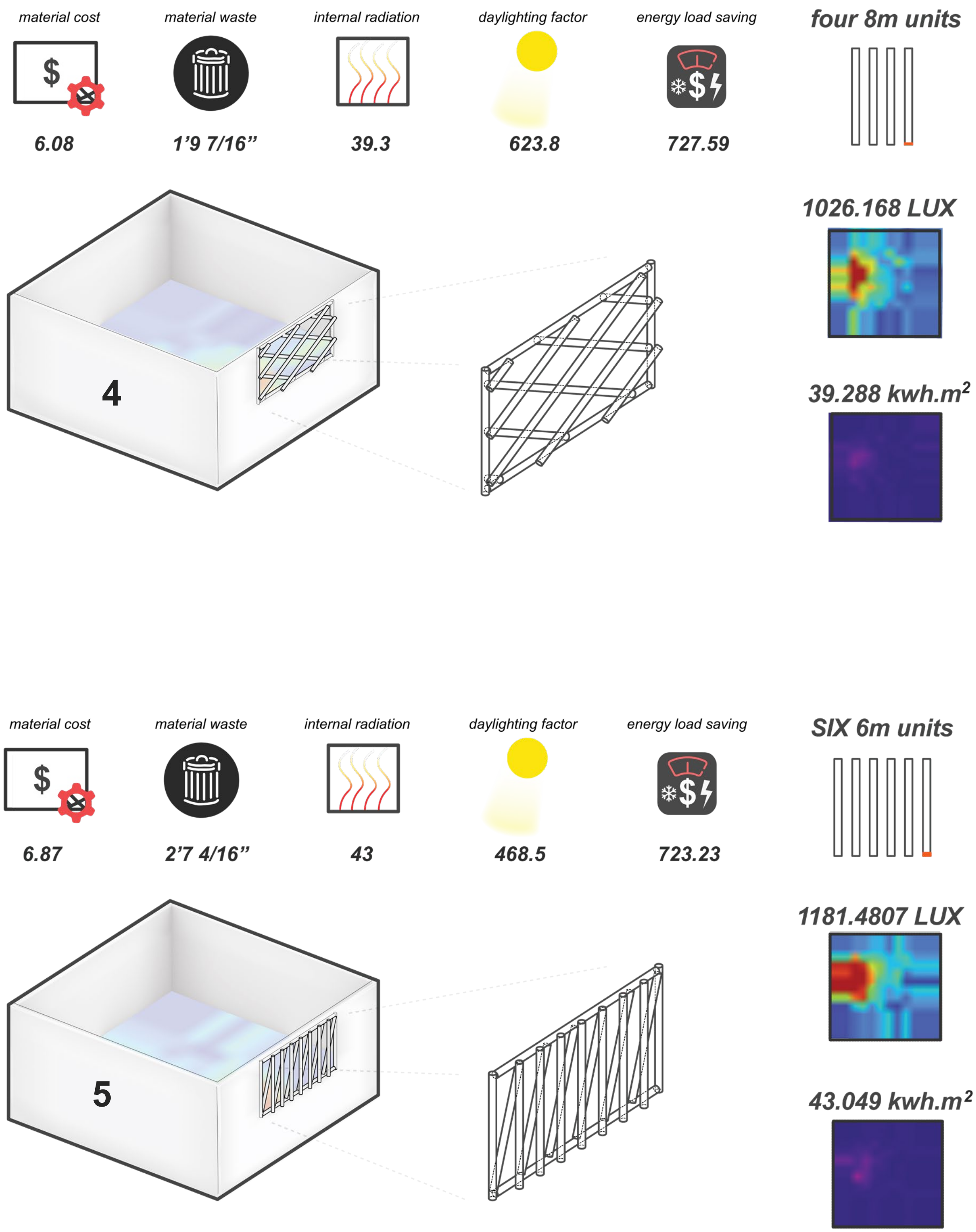
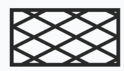


Figure 21.5 Pre-Study for GP Model Variable: POC Screen Type & Configuration

Table 4. Pre-Study Screen Results

m.$	rad	dl.diff	e.saving	m.waste	diff.sum & rank	notations
6.30 +104	30 +219	804.9 +172	-724.94 +11.68	1'4 10/16" +0	1 = 506.68 	lowest diff % sum lowest waste Lowest Material Cost w/ plausible variability
8.50 +140	24 +175	711.48 +152	-722.72 +13.90	1'10 1/16" +133	4 = 613.90 	second highest diff. % sum
9.84 +162	13.7 +0	1078.6 +230	-736.62 +0	1'9 9/16" +130	2 = 522.00 	has 2 best values: e.savings & rad
6.87 +113	43 +314	468.5 +0	-723.23 +13.39	2'7 4/16" +188	5 = 628.39 	Highest Waste and diff. % sum lowest dl diff.
6.08 +0	39.3 +287	623.8 +133	-727.59 +9.03	1'9 7/16" +129	3 = 558.03 	2 variable values * 2 sliders Lacks Variability. lowest material cost

key: optimal | difference | Best | Rank

Table 4. Pre-Study Screen Results. Screen Type 1 selected

Figure 21.3 POC - GP Model Variable Screen Component Definition Workflow

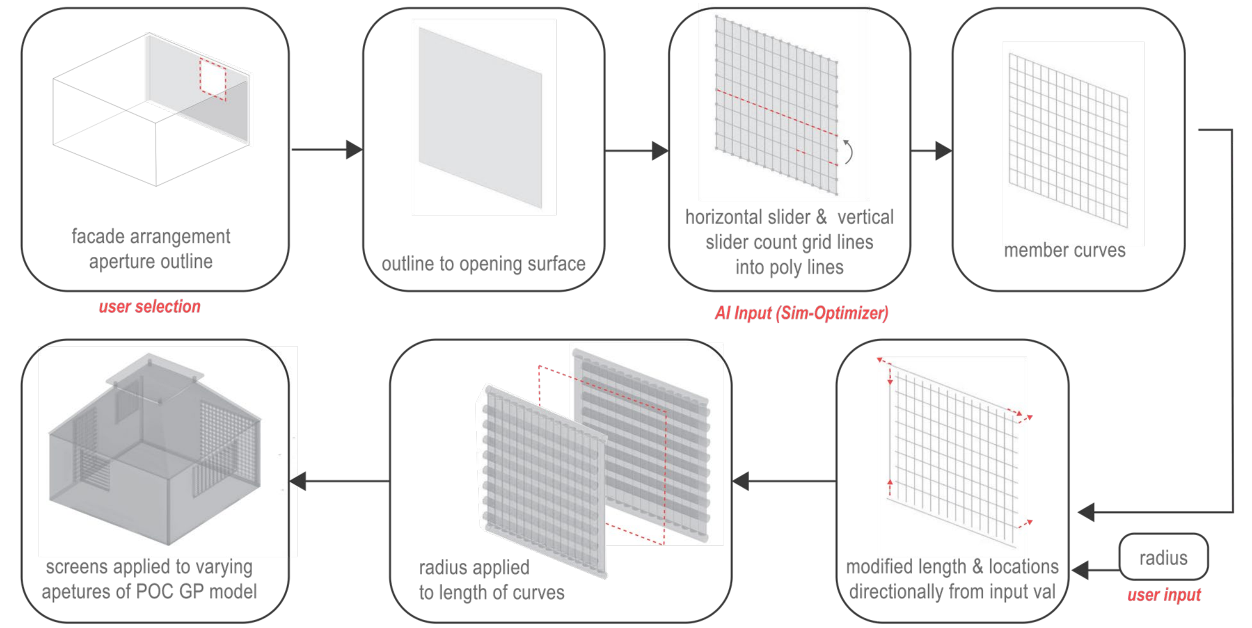


Figure 21.3 POC - GP Model Variable Screen Component Definition Workflow

Figure 21.4 POC - GP Model Material Cost Defined

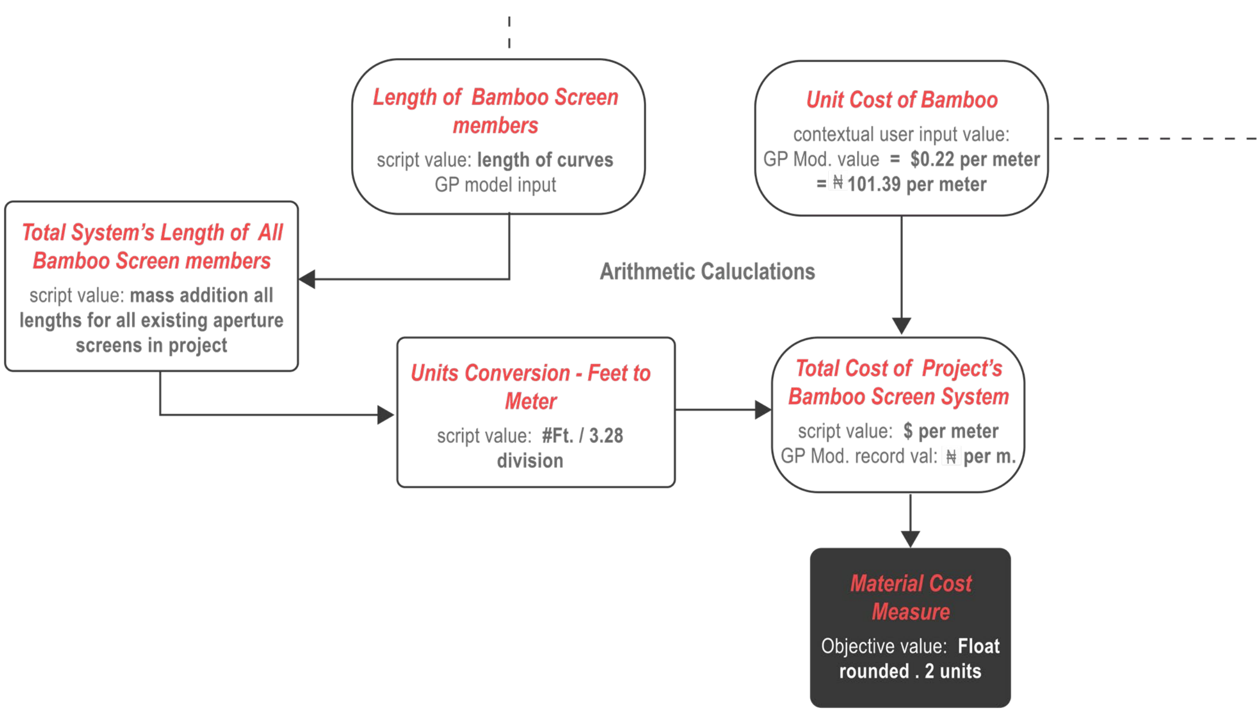


Figure 21.3 POC - GP Model Material Cost Defined Workflow

3.4 PORTION 2: SIMULATIONS & CALCULATIONS

With the base screens represented *(Figure 21.3),* the geometric aspect of the GP model is ready for testing and generated modifications, and the next portion of the framework script comes into play: simulations and calculations. To develop a useful shading device design, capturing the measures of environmental performance focuses on the metrics which affect user comfort, mechanical load requirements, and subsequent operational costs per year. These metrics are daylight illuminance (lux) mean interior radiation factor of the solution. The measures regarding cost efficiency focus on metrics reflecting the fixed cost of materials: the total cost of the screen set. It also includes the values building operational cost as it relates to minimizing the mechanical loads specific to cooling as a result of the configured vernacular shading devices. In assessing these measures cost efficiency and occupant comfort will inherently be maximized in the best outputs. The tool used to capture the performance-based measures for metric values are simulation tools. Imitative software programs are applied for finite element analysis. FEA is the process of simulating the behavior of a part or assembly: the buildings configured screens, under given conditions: the values of Lagos climate remapped into a year of simulated study [102]. There are a variety of simulation software that measure specified performic criteria which are better employed to select objectives and design problems *(Table 5)*

Table 5. Denoted Validations for Simulation Software Selection by Analysis

Application	Objective	Tool	Performace Criteria	Material	Developers
Various	Analysis of energy consumption selection & sizing of HVAC equipment	DOE-2,BLAST, HVACSIM+	Energy & HVAC sizing	Unknown	Lawrence Berkley National Laboratory University of Illinois National Institute of Standards &Technology
Wall cavity Uknown	Analysis of airflow in & around building, polluntant emission & migration, natural ventilation, & air conditioning Two common approaches used are Compuation Fluid Dynamics (CFD) model abd Multizone Network Model	PHOENICS FLOVENT COMIS	Ventilation & indoor air quality	Unknown	Concentration, Heat & Momentum Limited Flomeries Incorporated Lawrence Berkely Laboratory
Shading Glazing	Geared toward electrical lighting design & evalution, Some models also provide for daylight evaluation some models also provide for daylighting evaluation, Some models also provide for daylighting evaluation, Common approaches used include Zonal Cavity method. Ray Tracing, or Radiosity Technique	RADIANCE LIGHT-SCAPE LUMEN MICRO	Natural & electrical lighting	Unknown	Lawrence Berkely Laboratory Lightscape Techniques Lighting Technologies
unknown	Application of building & room acoustics simulation tools extremely limited Approaches used include Finite Element Method (FEM) & Boundary Element Method (BEM)	COMET/acoustic MODELER TAP	Acoustical	Unknown	Automated Analysis Incorporation Bose Corporation Trane Company
Shading	SMA thermal model(kinetic performance) Neighborhood impact & configuration pattern	Ladybug Radiance	Solar Irradiation Incedent radiance	Shape memory Alloy (SMA)	Mostapha Sadeghipour Roudsari EnergyPlus, OpenStudio
Shading	Validation of two-way morphing concept	Grasshopper Abaqus™	Daylight FEM	SMP SMA	Mostapha Sadeghipour Roudsari EnergyPlus, OpenStudio
Shading	Unknown	Ladybug (Grasshopper)	Daylight Solar radiance	SMA	David Rutten, McNeel & Associates Hibbitt, Karlsson & Sorensen, Inc., (HKS)
Shading	SMA actuator	Irradiance for SketchUp	Energy	SMA	Unknown
Shading	Optimized patterns	Evolutionary Algorithm	Tessellation	Polarized Film (Liquid Crystal)	Unknown
Shading	Daylighting, shading, & mechanical performance evaluation. Configuration Optimization	On-site measurement DIVA for RHINO	Visible daylight transmittance Solar radiation transmittance	Woven Bamboo	Solemma
Shading	Integration of BPS (Building Performacne Simulation), optimization of algorithms, & electronic sensors with parametric building modeling	On-site sensor DIVA Grasshopper Iron Python	Energy Irradiance Daylight	Unknown	Solemma, David Rutten, McNeel & Associates, Unknown
Glazing	Switching temperature range	On-site measurement EnergyPlus	Incident radiance Energy	TC	U.S. Department of Energy's (DOE) Building Technologies Office (BTO), NREL
Glazing	SMA actuator working through thermal activation to control the deforamtion	Unknown	FEM	SMA	Unknown
Glazing Opaque Wall	ACRESS prototype evaluation	On-site measurements	Energy	PCM TP, PC, EC glazing	Unknown

Abbreviation: TC - Thermochromic; PC- Photochromic; EC- Electrochromic; TP- Thermotropic; FEM- Finite Element Method

Table 5. Denoted Validations for Simulation Software Selection by Analysis Derived from [103,

The selected simulation tool for this thesis is Solemma's Climate Studio (CS) which was formerly known as DIVA. It's Built on EnergyPlus and a Radiance-based path tracing technology, the software boasts time quick and accurate simulations. Radiance-based path tracing technology according to ChatGPT, is a method of computer graphics rendering that simulates the behavior of light as it interacts with surfaces in a scene. Path tracing works by tracing many individual rays of light as they bounce around the scene, calculating their interactions with different surfaces and materials along the way, until they reach a virtual camera or light source. According to the studies in *(Table 5).* Climate Studio best fits the application for analyzing shading devices for the objectives of integration of BPS, optimization of algorithms, and sensors with parametric building modeling, although all will be virtual in this case. It is also the best fit for the evaluation of daylighting and HVAC – energy load calculations due to the deployed technologies of the software.

All CS simulations utilized require a Climate Studio scene layers model which resolves connectivity between the zones and assigned windows and boundary conditions as they relate to the parent surfaces. The parent surface information is borrowed from the parametric geo model in rhino-grasshopper. The software comes with thousands of construction assembly components, materials, templates, and specifications from real-world validated industry sources like ASHRAE standards, DOE benchmarks, and IDGB façade glazing products. For the POC study, the geo model is applied materials: earthen walls, and bamboo applied to the model are selected from the validated qualifications as vernacular resources via research and analysis of the context *(Figure 20).* The contemporary version of this GP model references the style of home found during a visit to Lagos in December 2022. Although there are many optimization frameworks, most generative frameworks cater to climate solutions or costs, some incorporating both (*Table 6).* The various simulations utilized to obtain the values required for climate and cost optimization are a daylight model (DL), radiation (RAD) model, and energy model (LOAD). The measures are simulated with the sensor grid with 81 sensors on an approximately 10.5ft^2 surface (*Figure 23.0, 23.2*).

Figure 23 POC - GP Model CS Simulations Settings

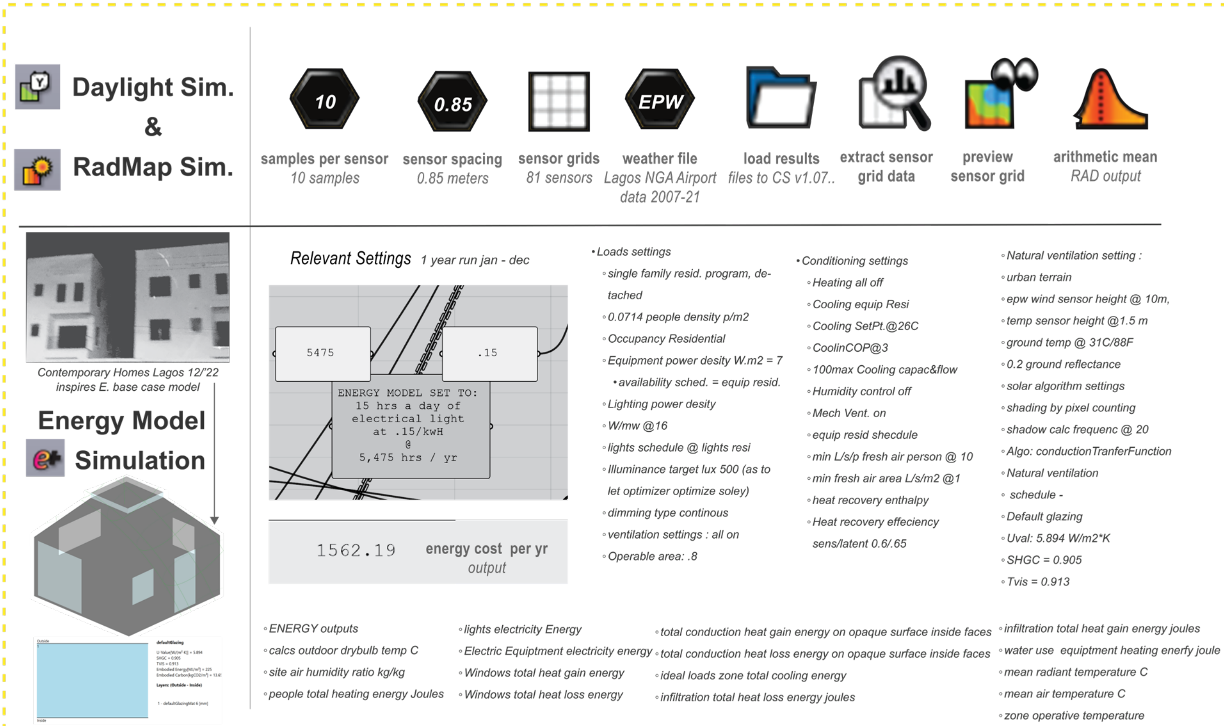


Figure 23 POC - GP Model CS Simulations Settings

Figure 23.2 POC - GP Model into Simulations and Calculations Workflow

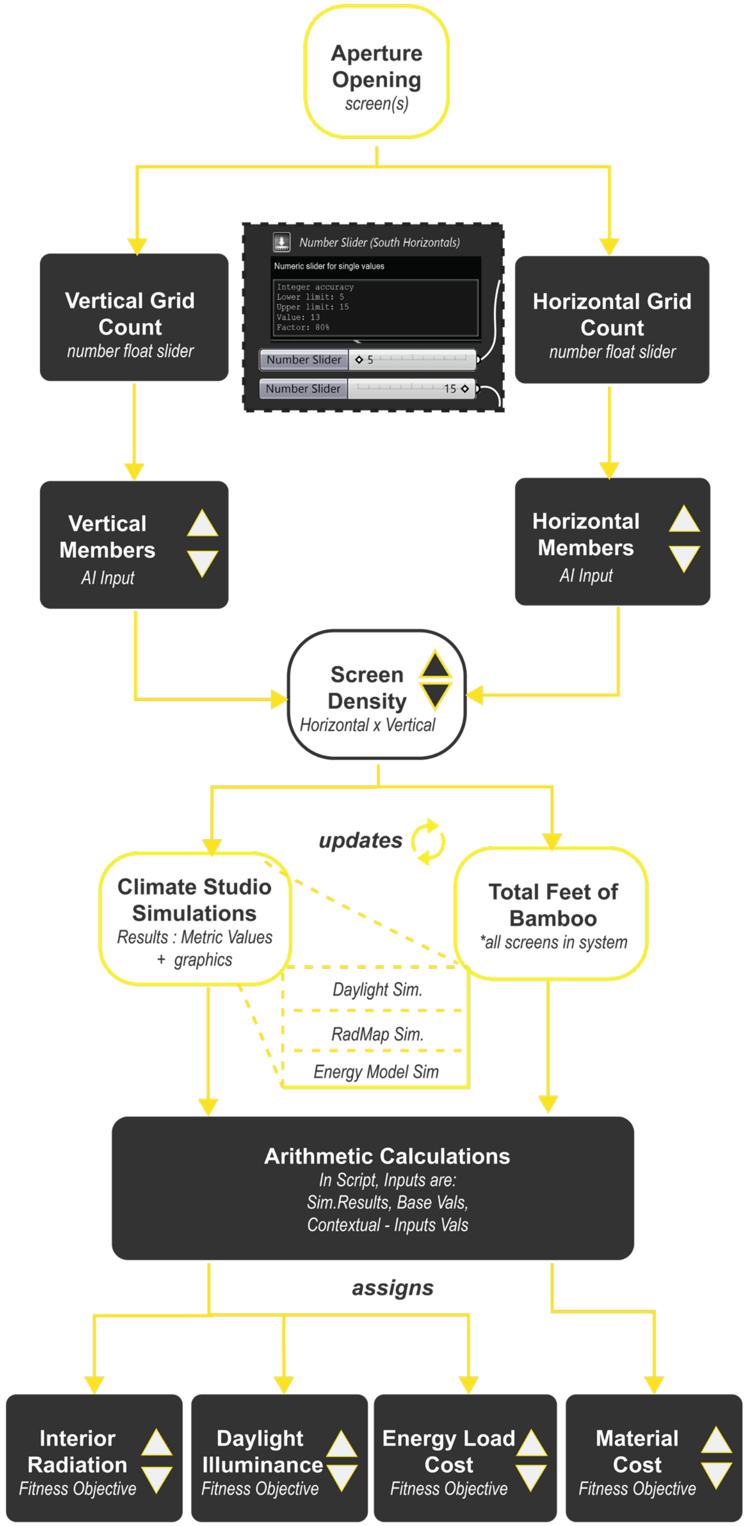


Figure 23.2 POC - GP Model into Simulations and Calculations Workflow

The DL model utilizes Adaptive Lighting for Alertness (ALFA) Circadian lighting design software. It simulates the non-visual effects of light in a space such as melanopic lux (EML). And can predict EML, the models selected output metric is the SI unit of illuminance (LUX), the calculation of how much light as lumen, falls unto a surface, measured per square meter. The year of data is run by a grid of 10 sensors for the sake of efficiency, and the output is an average of the simulation run. The output metric for the configuration is then differenced from the midpoint of the widely accepted task specific ideal lux range *(Figure 24.0)*. This base value of comparison is validated by the findings outlined in the referenced table (*Table 6*). The performance of visual tasks of low contrast/small size has a recommended lux range of 1000 – 2000 which is where the midpoint falls, as well as the metrics of the projects results. This is relevant as a goal value for optimization in low-income communities as homes are often also the place where a living is made and vice versa, particularly crafts and learned traditional trades which are very detailed tasks. The interior radiation (RAD) factor is taken from the simulation output as the average kilowatt hours per meters squared per year (Kwhm^2/yr.), this factor is recorded for visualization purposes. But this is then parametrically multiplied by cost of energy and area in meters squared according to the outputs of the shoebox energy model *(Figure 24.1)*.

Table 6. Illuminance (lux) recommendations

Task	Recommended Range
Computer-based tasks	100 - 300
Paper-based tasks	200 - 600
Maximum values	1280 - 1800
Working spaces with occasional visual tasks	100 - 200
Performace of visual tasks of high contrast / Large size	200 -500
Performace of visual tasks of low contrast / Small size	1000 - 2000

Table 6 Derived from [88]

The radiation and DL metrics are both minimized in large as to increase the level of occupant comfort they are both built into the cost factor of the Energy Model. External to the simulation, contextually in Nigeria, households may receive 5-8 hours of electricity per day at 135 kwh consumed per month per household with an average of 5 per capita. This means the rest of the Nigerian working day of 8 hours will need to be provided for with natural daylighting. It's also especially key in Lagos and other underdeveloped communities because electricity is not stable and often the power source is rendered ineffective several times a day, sometimes for several hours. Most people in Nigeria who can afford it, have a backup source, usually a powered generator. The cost of energy as of the study conducted in 2018, is around 7 US cents per kwh. "Those who have income spend about 7% per capita to obtain electricity, with only 59% of households having electricity in their dwellings". 1 hour of daylight in this context (not calculated from the energy model) can save $1.87 or ₦860.99 per household [54]. The conclusion is that daylighting is applicable to a problem regarding heat mitigation and affordability, the goals of this measure can be inverse depending on the configuration. While internal radiation reduction is desired as it is necessary to mitigate thermal discomfort, especially in an overheated geographic context. The CS energy model utilizes a full-fledged UI with default values, and the full function of the user selection for its advanced settings is extensive (Figure 23). Vernacular energy model settings are changed from that of the Contemporary model, to reflect the characteristics of the two models. In the compared vernacular settings, the natural ventilation is on an all on schedule, with cross-ventilation and stack driven ventilation assigned based on the design and allowance of air flow within the apertures on façade and roof. The output results of the energy model include EUI value as kwh/m^2/yr., AIA 2030 challenge Baseline EUI value, Co^2 operational emissions as kgCO^2/m2/yr. The results used as inputs for the functions to calculate the objectives for optimization are cost of operational energy as \$/m^2/yr., The area of the structure is modeled as m^2. The rest of the outputs are utilized for the graphic output of the CS model which has been set to showcase the breakdown of energy consumptions: equipment, fans, light, hot water, and heat throughout the year *(Figure 24.2).*

Figure 24.0 POC - GP Model Daylight Illuminance Defined

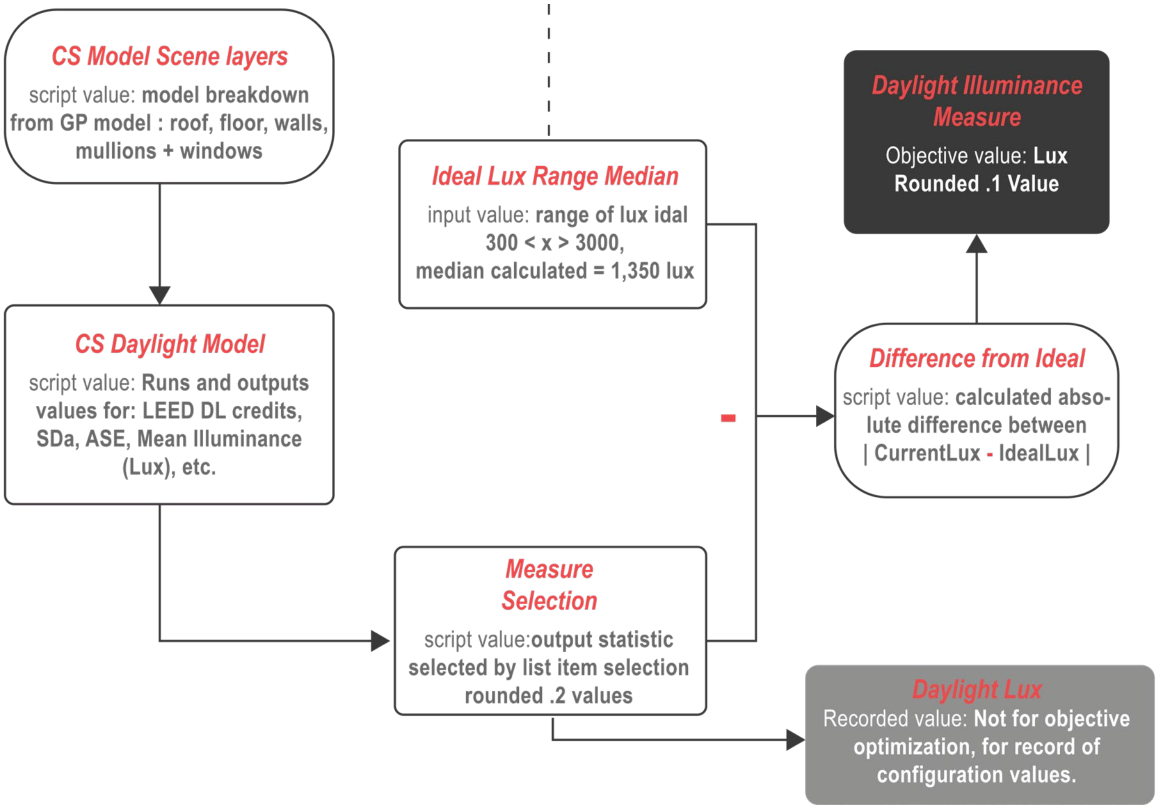


Figure 24.0 POC - GP Model Daylight Illuminance Defined Workflow.

Figure 24.1 POC - GP Model Radiation Defined

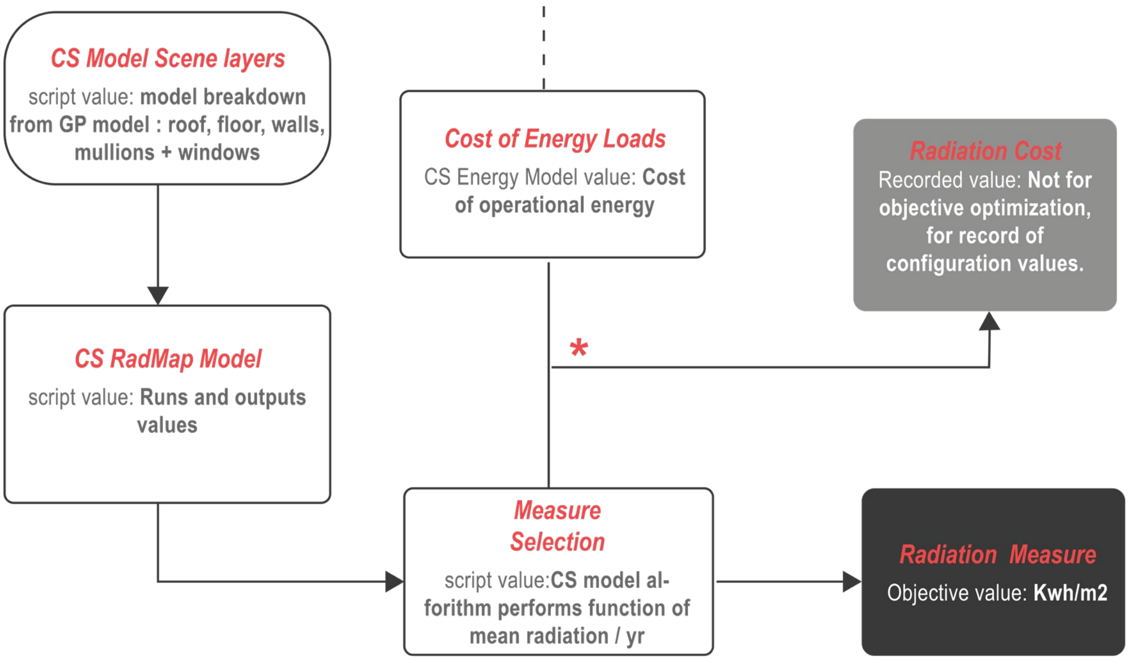


Figure 24.1 POC - GP Model Radiation Defined Workflow

Figure 24.2 POC - GP Model Energy Cost Defined

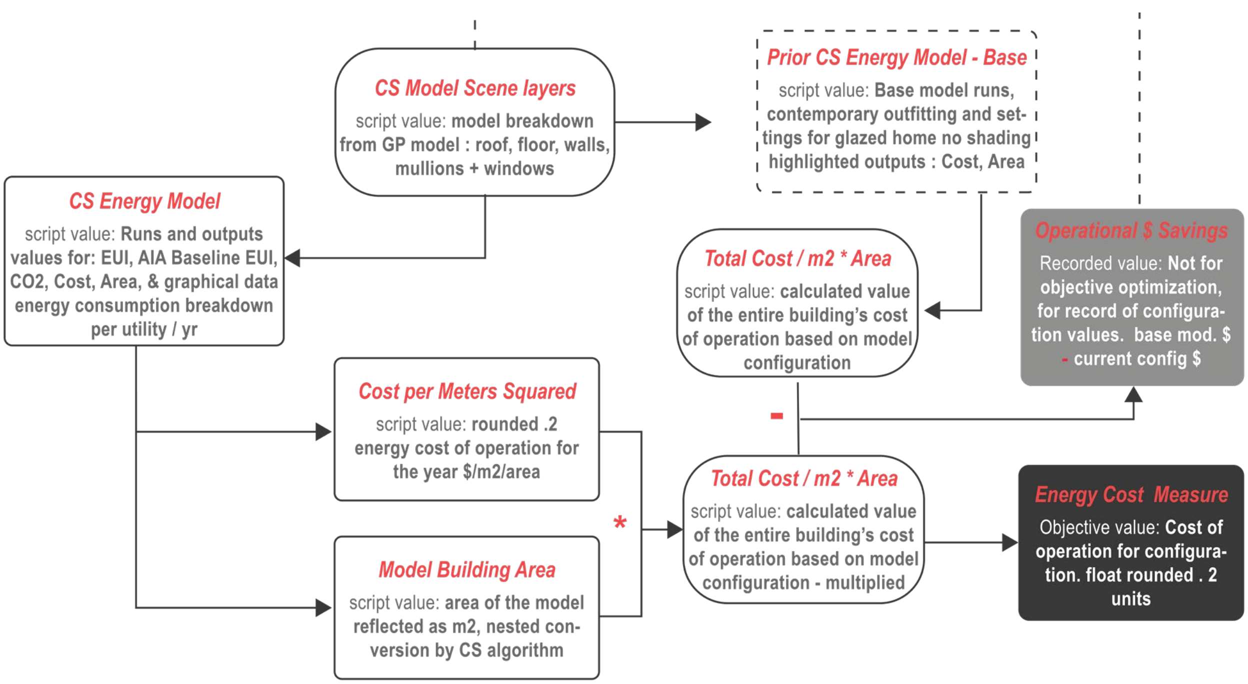


Figure 24.2 POC - GP Model Energy Cost Defined Workflow

3.4 PORTION 3: OPTIMIZATION

With the objectives defined by simulations and calculation the metrics are then in the appropriate format for the problems' goals as objective fitness values (*Figure 21.4, 24.0, 24.1, 24.2*). These are characterized as genotypes in this evolutionary process, and outputs as phenotypes *(Figure 0.6).* The optimization engine integrated into the visual programming environment *Grasshoppe*r is *Octopus* [99]. The evolutionary computing engine was developed by Robet Vierlinger to be a multi-objective version of the single-objective Galapagos optimization engine by Davis Rutten. Its objective space employs the Pareto Principle which allows for a search for multiple goals at once. The principle simply states that for many outcomes, roughly 80% of consequences come from 20% of causes also known as the "vital few"(*Figure 25*)[102].According to food4rhino, the software allows for: trade-offs between 2+ number of goals, recorded history, exported files, data save within grasshopper document, objective change during search, interaction with the 3d model in objective space, a variety of visual feedback choices, and preferred solutions can be selected utilizing the user interface developed by Christopher Zimmel. Out of other options such as Galapagos, Goat, Tunny, Optimus and Wallacei, the software was most compatible with the needs and characteristics of this optimization problem. Other software's were faulty in their development, incompatible with other integrated software such as simulators, or did not accommodate for multi-variable optimizations. The various engines also made available the selection of the applied algorithm; this factor went into the selection of Octopus as well. Some of the other algorithms that vary based on selection methods, crossover methods, mutation rate determinations, elitism inclusion, population size determination, Fitness function objective space construction, and genetic encoding methods, are: jEDE, RbfOpt, Bayesian – TPE, Grid Bayesian – GP, NSGA-II, CMA-ES, Quasi-MonteCarlo, SPEA, HypE. The latter two are employed by Octopus and were developed at ETH Zurich *(Figure 25.5*) [106, 107, 108].

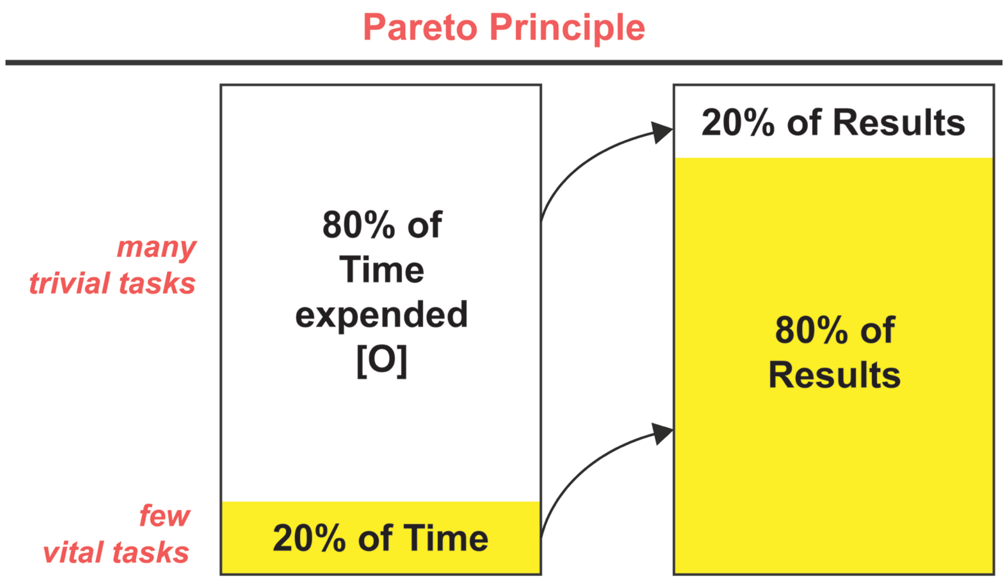


Figure 25. Pareto Principle

Figure 25.5: Figure of Tables Comparing Optimization Algorithms

Optimization Tool	Algorithms	Characteristics
Wallacei	• Simple Genetic Algorithm (SGA) • Multi-Objective Genetic Algorithm (MOGA) • Non-Dominated Sorting Genetic Algorithm (NSGA-II) • Particle Swarm Optimization (PSO) • Simulated Annealing: Simulated Annealing (SA) • NeuroEvolution of Augmenting Topologies (NEAT)	single & multi-objective fitness functions probabilistic, sensititve to parameters search space stochastic - randomized population based artificial neural networks (ANNs) interface
Galapagos	• Multi-Objective Genetic Algorithm (MOGA) • Non-Dominated Sorting Genetic Algorithm II (NSGA-II) • Differential Evolution (DE) • Evolutionary Strategy (ES)	(MOGA) variant multi-objective fitness functions pareto fronts well developed interface population based, search space
Optimus	• Simple Genetic Algorithm (SGA) • Non-Dominated Sorting Genetic Algorithm II (NSGA-II • Multi-Objective Genetic Algorithm (MOGA) • Justification-based Differential Evolution (jEDE)	(DE) variant ranking multi-objective fitness functions population based, search space pareto fronts justification functions (for constraints)
Oppossum	• Non-Dominated Sorting Genetic Algorithm II (NSGA-II • Strength Pareto Evolutionary Algorithm (SPEA2) • Derivative-free Radial Basis Function Interpolation (RbfOpt)	(RBF) variant multi-objective fitness functions population based, search space, pareto fronts well developed interface RbfOpt for black-box, non-linear, & non-convex objective functions,
Tunny	• Non-Dominated Sorting Genetic Algorithm II (NSGA-II • Multi-Objective Genetic Algorithm (MOGA) • Evolutionary strategy(CMA-ES) • Bayesian Optimization (TPE) • Grid Bayesian Optimization (GP) • Quasi-MonteCarlo	stochastic- randomized multi-objective fitness functions population based, pareto fronts, user interface gradient based (gradient descent, conjugate gradient, and quasi-Newton methods) surrogate based search space w/ interpolation for black-box functions
Octopus	• Strength Pareto Evolutionary Algorithm - Epsilon (SPEA-E) • Hyper-Volume Estimation (HypE) • Quasi-MonteCarlo • Non-Dominated Sorting Genetic Algorithm II (NSGA-II • Multi-Objective Genetic Algorithm (MOGA) • Particle Swarm Optimization (PSO) • Differential Evolution (DE)	multi-objective fitness functions population based, pareto fronts, well developed user interface epsilon-dominance relation - variant of Pareto-dominance SPEA-E * HypeE for multiple, conflicting objectives & non-linear, non-convex, or discontinuous objective functions. HypE for discontinuous objective functions, low dimension prob. hypervolume objective search space

Foundational Genetic Algorithms

Algorithm Name	Type	Selection	Crossover	Mutation	Elitism
Simple Genetic Algorithm (SGA)	Generational	Roulette Wheel	Single-point	Bit-flip	Optional
Steady-State Genetic Algorithm	Steady-state	Tournament	Single-point	Bit-flip	Optional
Multi-Objective Genetic Algorithm (MOGA)	Generational	Non-Dominated Sorting	Simulated Binary	Polynomial	Optional
Differential Evolution (DE)	Generational	Random	Differential	Uniform	Optional
Genetic Programming (GP)	Generational	Tournament	Subtree Crossover	Subtree Mutation	Optional
Evolution Strategies (ES)	Generational	Truncation	Gaussian	Self-adaptive	Optional

Figure 25.5. Comparing Optimization Algorithms. References [65]

Figure 26 Optimization HypE Algorithmic Loop Detail

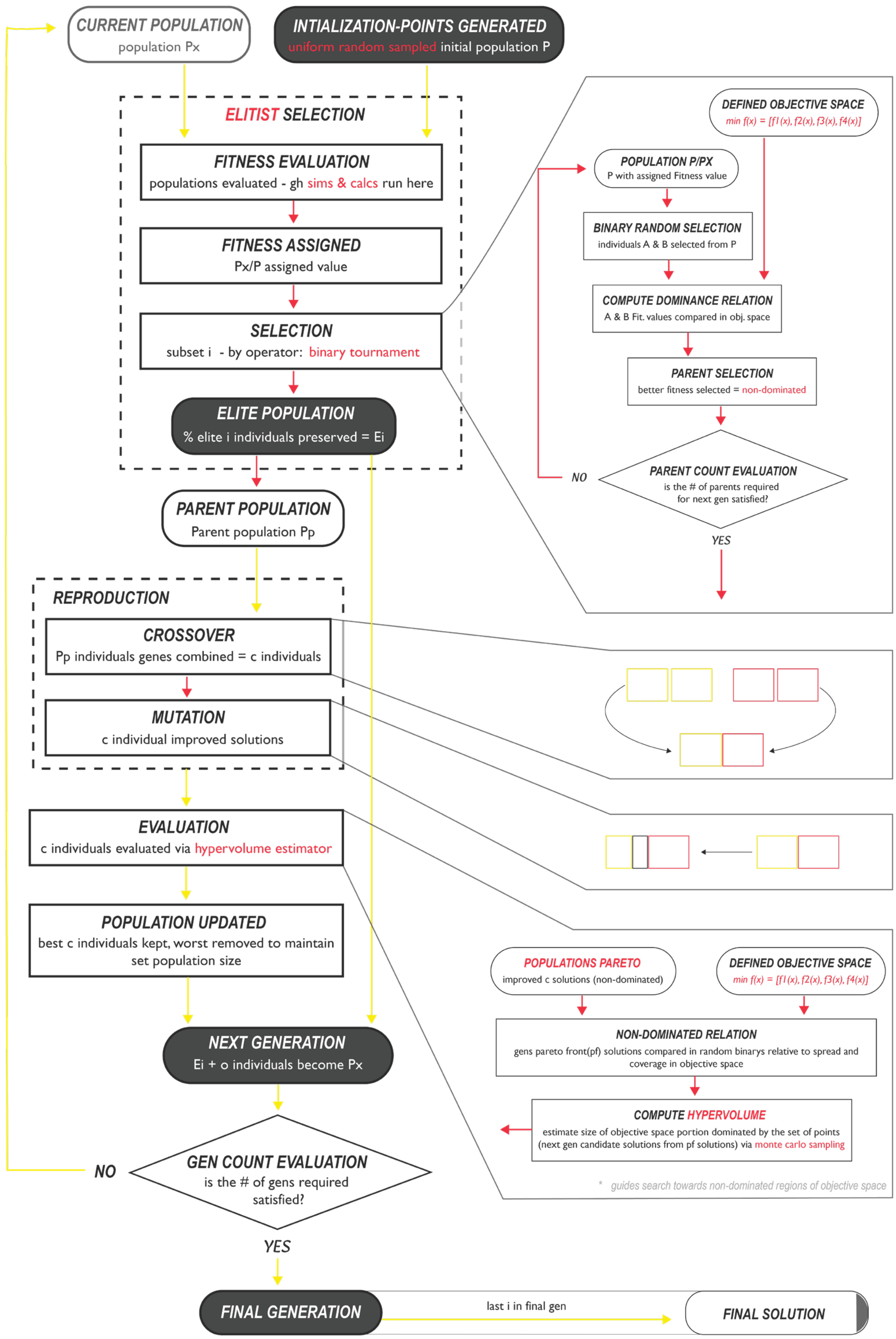


Figure 26. POC – Optimization HypE Algorithmic Loop Detail. References [101, 106 – 110]

Optimization algorithms assign a purpose to the generative design process and add efficiency to the design development process. The selected settings of the algorithm within the POC-developed framework perform a search of the remaining parameter space. The process and performance of the optimization engine highlighted in detail the step-by-step flow of the loop which operates on the fitness function as a defined objective space: min f(x) =[f1(x), f2(x), f3(x), f4(x)] (Figure 26). The function's minimized values are: f1(x) = daylight illuminance, f2(x) = radiation, f3(x) = energy cost, f4(x) = material cost. The population of generations goes through an elitist process that outputs the best and preserves their genetic information encoded throughout the rest of the generative process *(Figure 0.7).* The elitist selection process utilizes a binary tournament operator which selects two random individuals to compare for parent selection. The comparison is a calculated dominance relation where the better fitness is selected and therefore the most non–dominated option. Non-dominated means that the values do not lean towards one fitness value or another but instead strive towards a well-rounded value that appeals best to all fitness values. Reproduction happens when parents are selected, this hosts the crossover and mutation process where genes are combined and improved with other solutions genes. Evaluation occurs evaluating for the best non-dominated which is the Pareto front (*Figure* 27). Once the population is updated the next generation begins. The number of gens set is embedded within the framework optimization space as 30 this is checked at the end of each generation. Once the count is fulfilled the optimization stops and apart from the elitist determinations by Octopus's HypE algorithm (mutation and reduction), the best solution is found as the last population individual in the last generation.

Figure 27. POC – Algorithm Settings and Displays

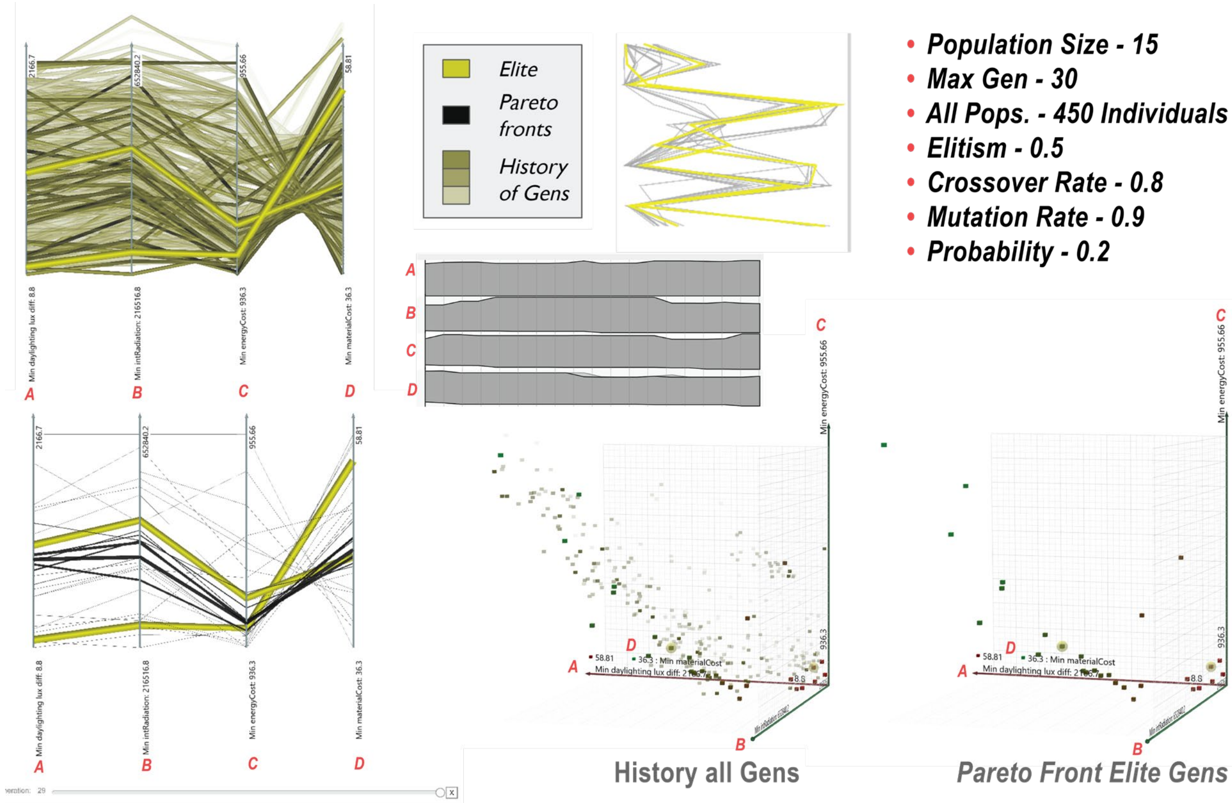


Figure 27. POC – Algorithm Settings and Displays

3.5 DATA VISUALIZATION & RECORDING

Figure 28 A & B. Solution Selection Workflows

Figure 28 a. Optimization Results Selected Reinstated

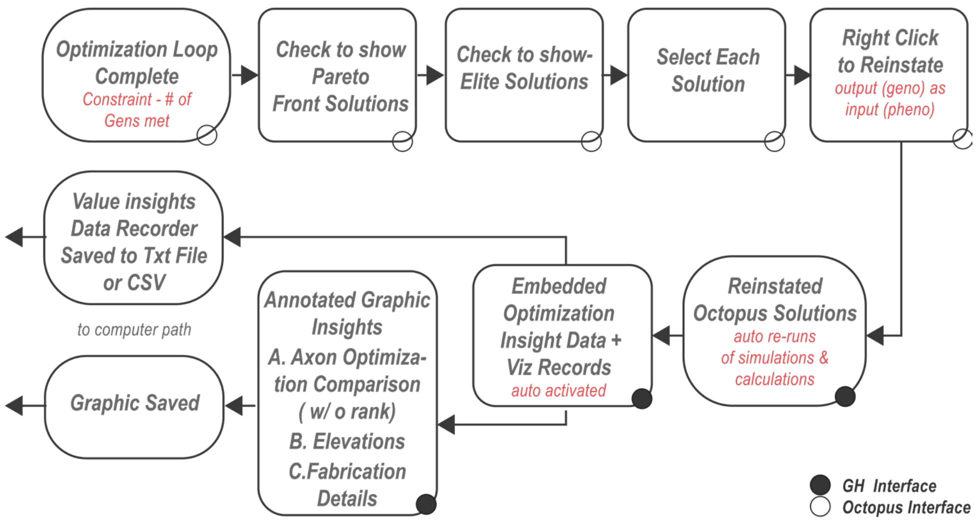


Figure 28 b. Optimization Results Selected Exported

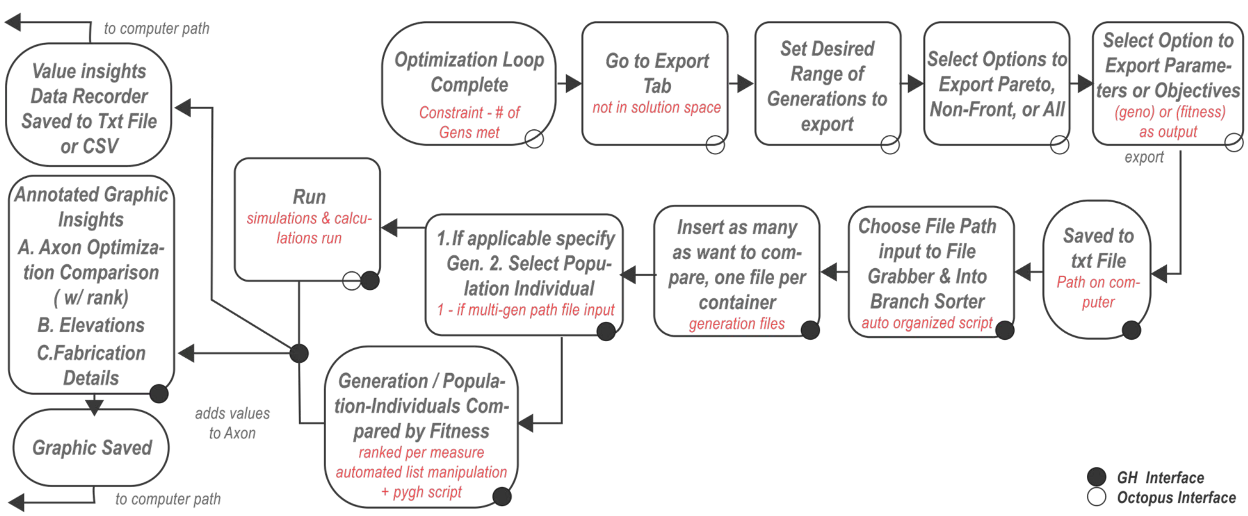


Figure 28. POC – Result Selection Workflows

Although there are many workflows and options, 2 result selection and recording methods and workflows have been defined for this Proof-of-Concept study. The first allows any range of population individuals and generations Pareto principle activated or not), to be selected and exported as a data file which can later be uploaded into the grasshopper interface. The reinstatement option occurs from the Octopus interface which simultaneously updates in Grasshopper. These selections are then processed for various visualization and data recording *(Figure 28).* The graphic and quantitative and qualitative records allow the user to digest the design output and decide and plan. The purpose is to inform and expand the applications of the framework. The files saved to a computer path can then be reformatted and or directly uploaded into other software where the varying forms of data can be implemented, manipulated further, specified, or visualized. For example, a CSV file can be exported to Revit for fabrication and building information modeling detailing, take-off sheet configuration with prices, sizes, and other visuals formatted by industry standards. The graphic outputs with noted specifications are legible for non-designers and for those familiar with architectural drawings (*Figure 29,30*).

Figure 29. Numerical Data Records

Figure 29. Numerical Data Records

Figure 30. Graphic Data Records

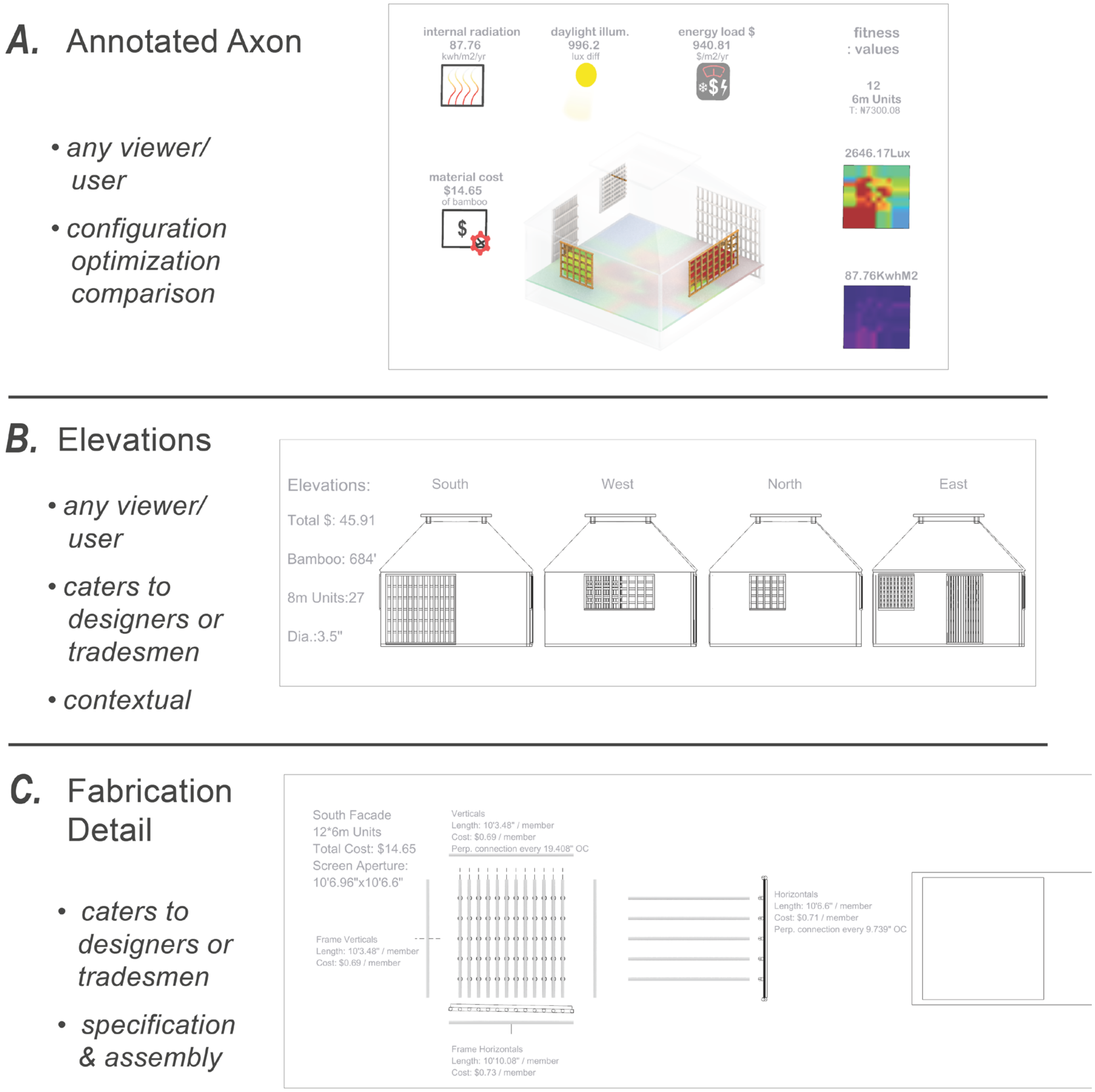


Figure 30. Graphic Data Records

CHAPTER 4. RESULTS

The results of the optimization run are displayed in Octopus's objective solution space. There were approximately 435 possible solutions generated, there are 28 individuals in the final generation which is the most resolved. 8 of these Pareto front individuals can be the best categorized as good solutions. 7 of them can be categorized as the best solutions while 13 of them sway between good and best. The determination of categorization of solutions into good - green, and best - red is embedded into the hype algorithm of Octopus (*Figure 26)*. It is likely based on the combination between the dominance relation and the hypervolume indicator *(Figure 31.1).* The Pareto dominance relation is used to determine the dominance between solutions. A solution dominates another if it performs better in at least one objective and does not perform worse in any other objective. In the application of dominance, the algorithm identifies the non-dominated solutions that form the finalized Pareto front [65]. The good solutions which are green are categorized as non-dominated, meaning they also contribute positively to the hypervolume indicator. "These solutions are considered good compromises, providing a diverse representation of the Pareto front" [65]

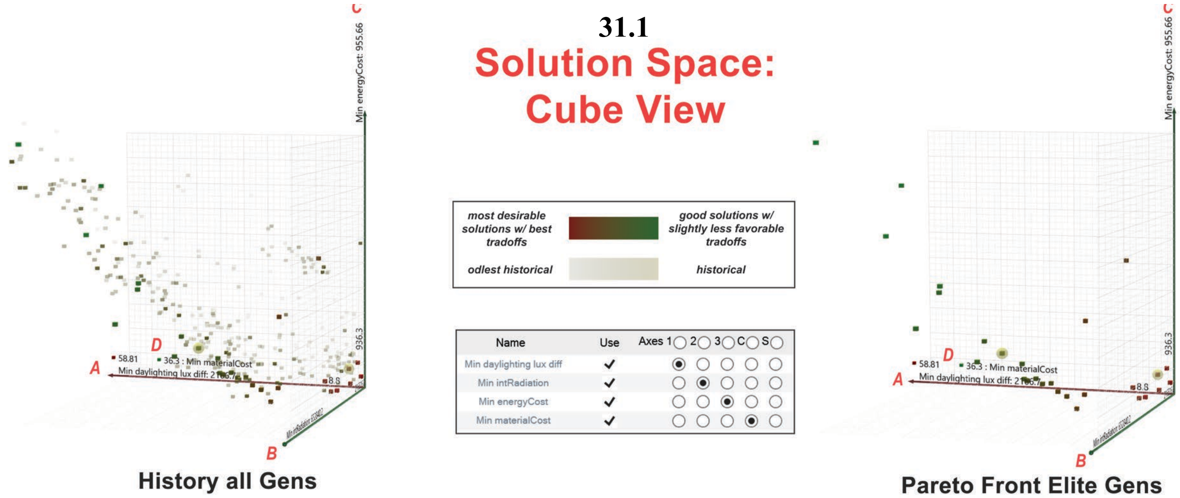
HypE's hypervolume indicator is a metric that evaluates the spread and quality of solutions in the multi-objective optimization. It measures the volume of the objective space covered by the set of solutions. The hypervolume indicator considers the trade-off between different objectives and rewards solutions that achieve a better spread and coverage of the Pareto front. The red represents the best-performing or most optimal because they have better trade-offs between the calculations of the objective values and comparisons within the algorithm. This categorization may be given to solutions that are top-performing or achieve the highest indicator values. The higher indicator value is influenced by the best equalized minimized metric outputs for the 4 objectives per solution: internal radiation, daylight illuminance difference, energy load cost, and material cost. The hypervolume indicator is a metric used in multi-objective optimization to quantify the quality and spread of solutions in the objective space. The measured volume of the objective space dominated by the set of solutions is determined relative to a reference point or reference set.

The exact mathematical formulation of the hypervolume indicator can vary depending on the specific implementation of the Monte Carlo sampling algorithm used in this case. The general and simplest calculation of the indicator: volume of the space enclosed by the Pareto front and a reference point or reference set is "H(R, P) = Volume(R - P). H(R, P)" is the hypervolume indicator value. "P" is the Pareto front, or the set of solutions being evaluated. These solutions are located in the multidimensional space relative to the axis representing the objectives (*Figure 31.1, .2*) Energy cost is referenced via the z axis and the other objectives are distributed between the x and y. in the formula "R" represents the reference point or reference set. The reference point or reference set "R" is defined based on the problem domain and the objectives of the optimization which are these axis assignments. This is used to establish a bounding region or reference front that helps the AI to calculate the volume of the objective space dominated by the set of solutions P. "R" is determined as an ideal set of multiple ideal points equaling 0, which represents the best possible values for the 4 objectives to be minimized. This covers the range of desired performance measures for a flexible and comprehensive evaluation of the optimizations hypervolume. The specific problem is made up of internal radiation, daylight illuminance difference, energy load cost, and material cost, and the desired characteristic of minimization for each lead to variations in the hypervolume indicator values and the resulting rankings of solutions. In the indicator formula, "Volume(R - P)" denotes the volume of the objective space enclosed by "R" and "P". Calculating the hypervolume indicator involves determining the extent of dominance of solutions in "P" over the reference point or reference set "R". The volume of the dominated space is then computed based on this dominance relationship. In Octopus's hypE framework the inverted hypervolume indicator or the incremental hypervolume indicator are not utilized.

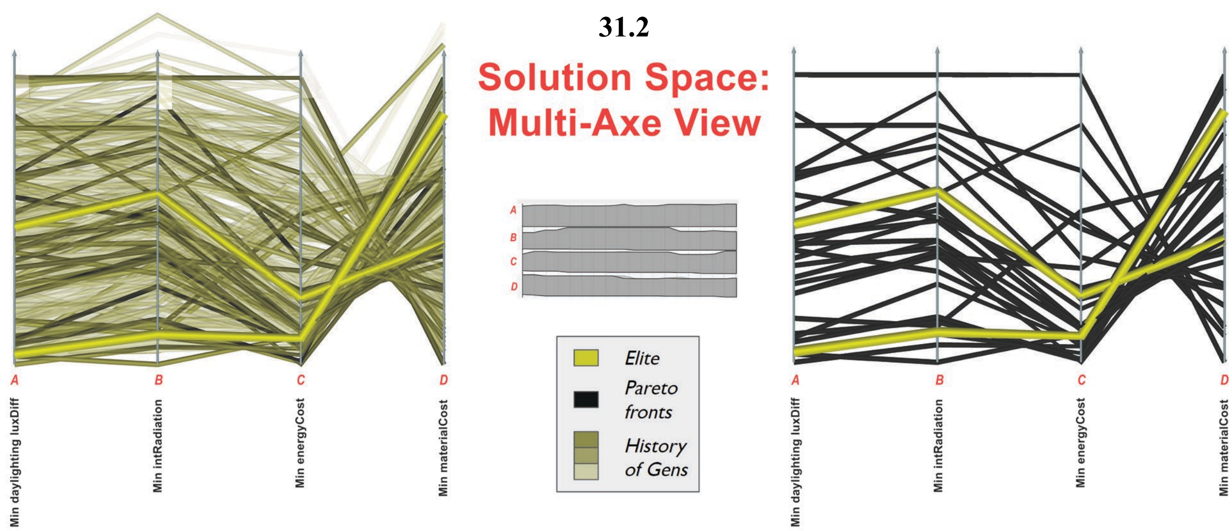
A solution can be both non-dominated and best indicated as non-dominance influences the indicator value. However, some solutions with lower indictor volume estimates are on a spectrum in between the visually differentiated categories. Those with the lowest indicators, and inherently high non-dominance relations are simply categorized as non-dominant “good” solutions within the Pareto Front. The most elite are determined by rank. Rank is established by proximity to the ideal set, the best possible values for each objective (0). The least dominated solutions are less crowded within the Pareto front and are generally ranked higher also. These elite solutions have great diversity, and objective goal achievement of the selection criteria to minimize. For this optimization problem result, the algorithm determined 2 out of the total Pareto to be elite solutions meaning they are the most optimal (*Figure 31.1,2,3,4*). These are highlighted in yellow within the solutions space views. The first is the most non dominant of the solutions near the 0,0,0 ideal, and ranked #1. The other is ranked #2 as it is in a central location between the range of values produced for each objective in the optimization run. It is the most non-dominated and equally valued, which is inherently the least crowded solution. Across the entire collection of results there was a significant range between the low and high values of the 4 objectives across solutions (*Figure 31.5).* The following project results include the data of annotated graphics of highlighted solution as determined by the optimization framework. Visuals and metrics will be displayed in the template format of the parametric visualization script components. Tables and charts of comparisons of the elite solutions are also displayed to show if the framework’s process worked as intended *(Figure 31.6, 32).*

Figure 31. Solutions Data

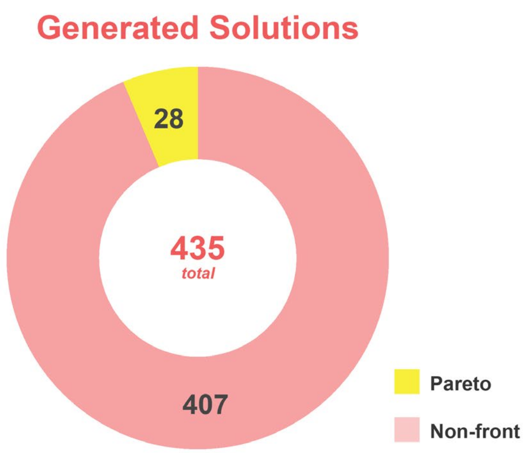
31.1

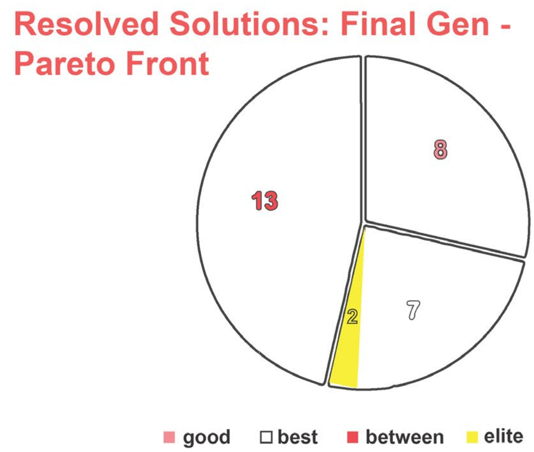


31.2

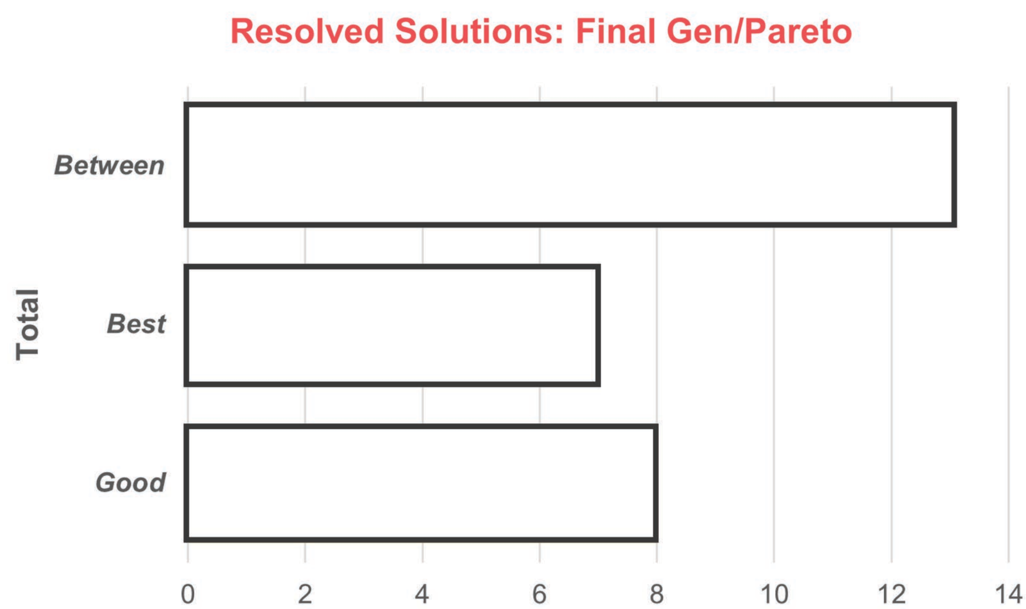


31.3

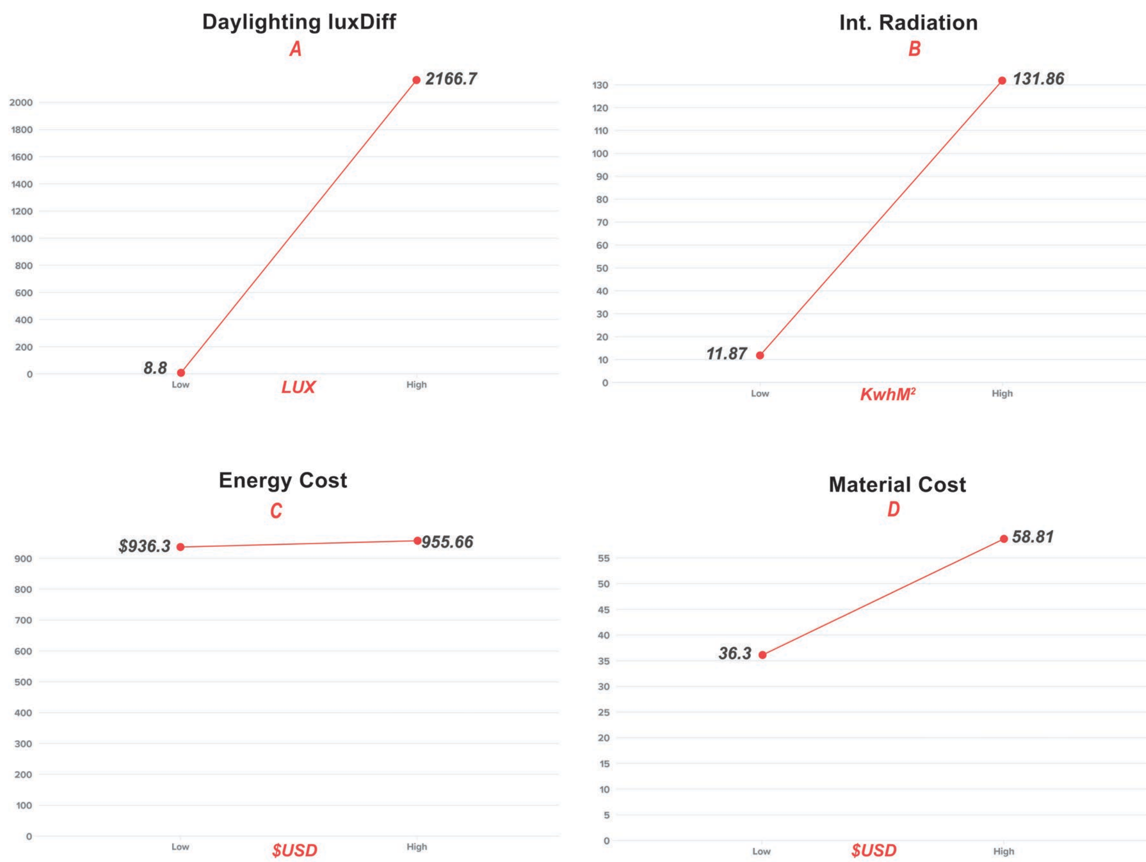

Generated Solutions
28
435
total
407
Pareto
Non-front


Resolved Solutions: Final Gen - Pareto Front
8
13
2
7
good
best
between
elite

31.4


Resolved Solutions: Final Gen/Pareto
Between
Best
Good
Total
0
2
4
6
8
10
12
14

31.5



31.6

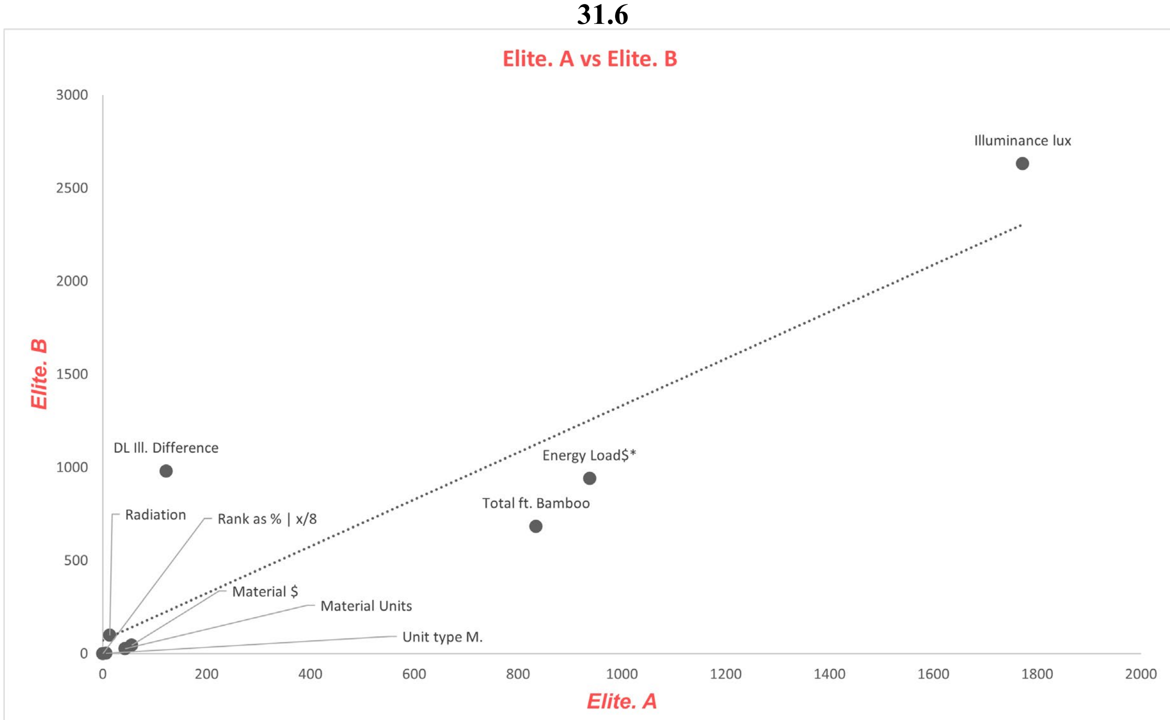


Figure 31. Elites A vs B Comparison; .1, .2, .3, .4, .5, .6

Figure 32. Elite: Most Optimal Solutions to Design Problem.

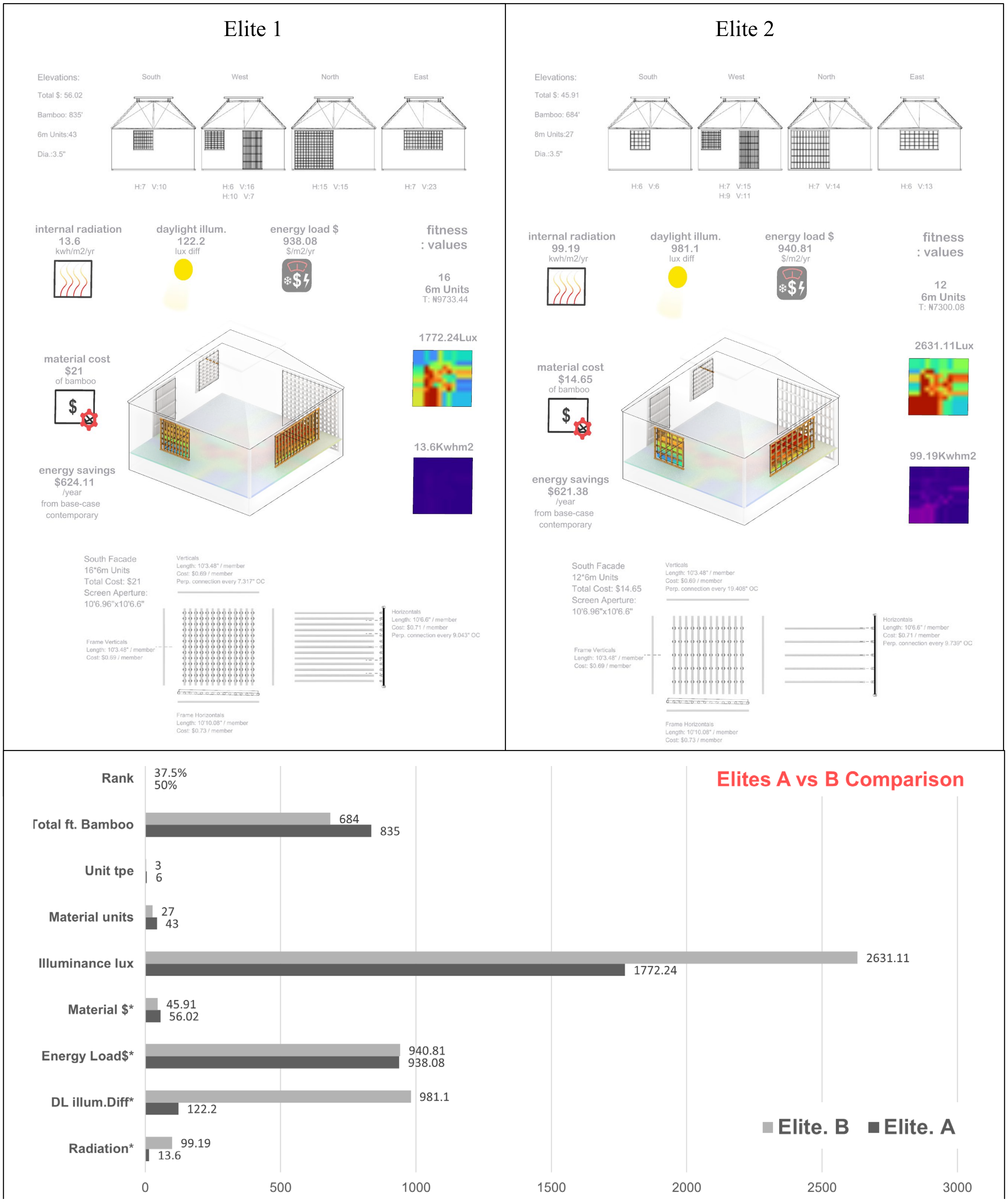


Figure 32. Elite: Most Optimal Solutions to Design Problem

Figure 33. Most Optimal

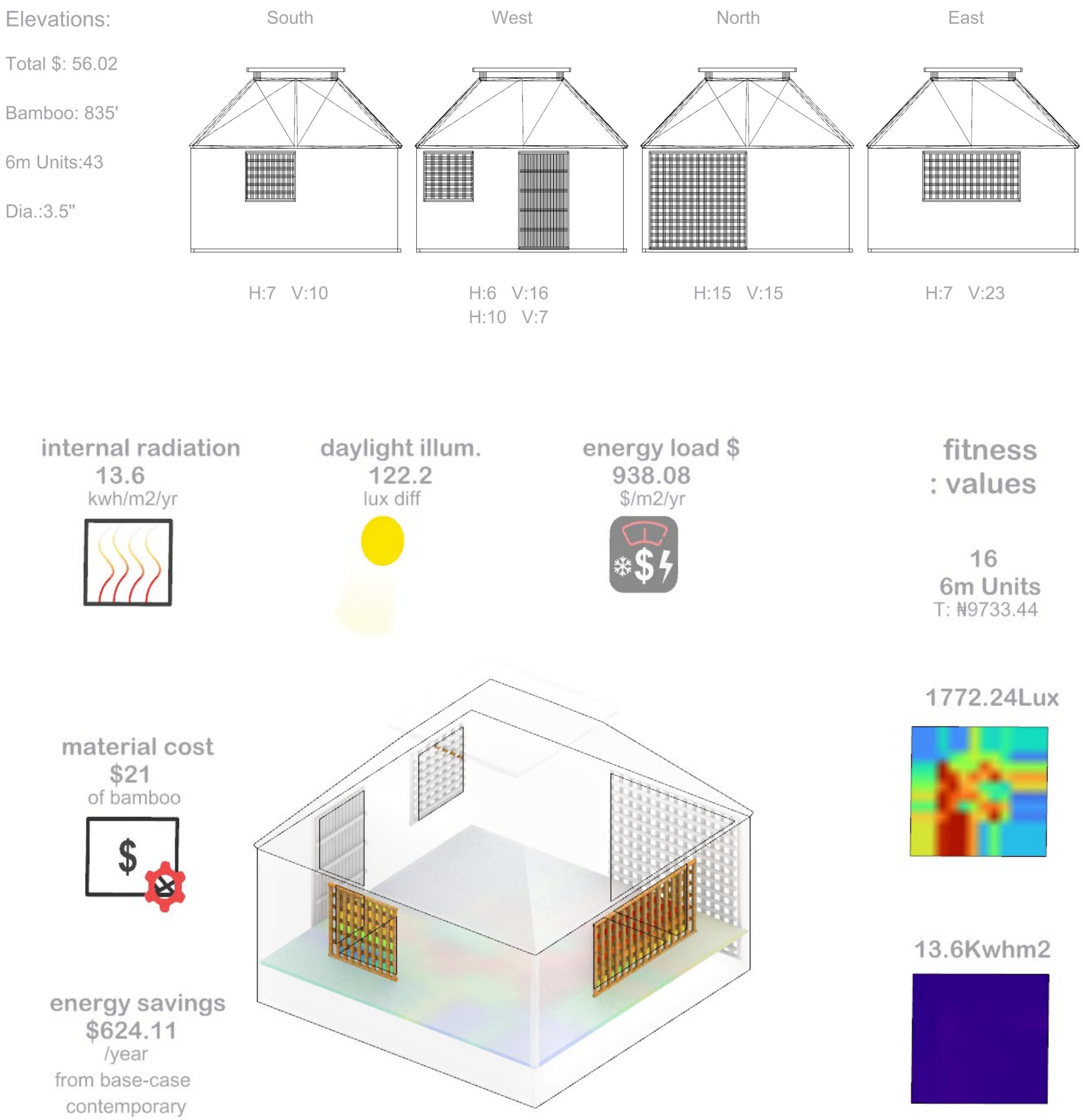
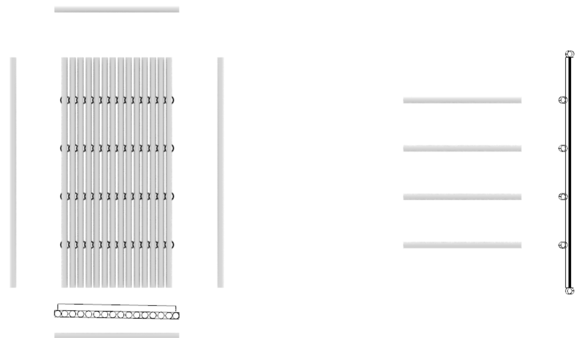


Figure 33.a Most Optimal Solution

East Facade
11*6m Units
Total Cost: $13.2
Screen Aperture:
5'3.36"x5'3.48"

Verticals
Length: 10'3.48" / member
Cost: $0.69 / member
Perp. connection every 22.879" OC



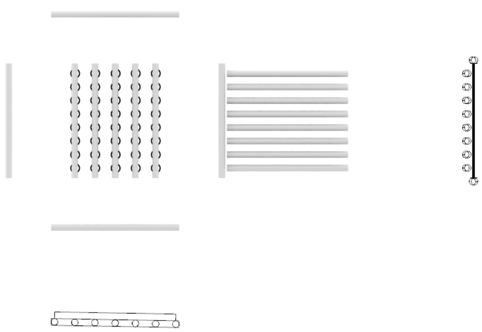
Frame Verticals
Length: 10'3.48" / member
Cost: $0.69 / member

Horizontals
Length: 5'3.36" / member
Cost: $0.35 / member
Perp. connection every 3.671" OC

Frame Horizontals
Length: 5'6.84" / member
Cost: $0.37 / member

4*8m Units
Total Cost: $5.92
Screen Aperture:
5'3.48"x5'3.36"

Verticals
Length: 5'0" / member
Cost: $0.34 / member
Perp. connection every 5.302" OC



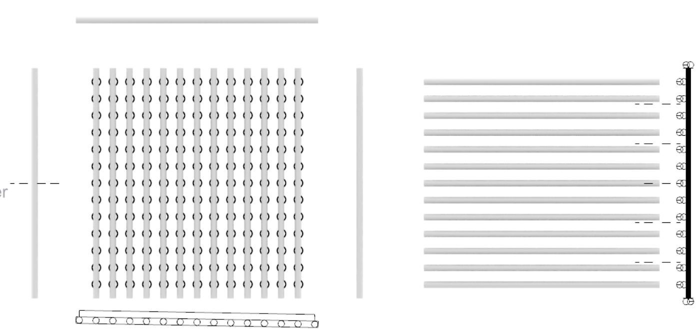
Frame Verticals
Length: 5'0" / member
Cost: $0.34 / member

Horizontals
Length: 5'3.36" / member
Cost: $0.35 / member
Perp. connection every 10.55" OC

Frame Horizontals
Length: 5'6.84" / member
Cost: $0.37 / member

South Facade
16*6m Units
Total Cost: $21
Screen Aperture:
10'6.96"x10'6.6"

Verticals
Length: 10'3.48" / member
Cost: $0.69 / member
Perp. connection every 7.317" OC



Frame Verticals
Length: 10'3.48" / member
Cost: $0.69 / member

Horizontals
Length: 10'6.6" / member
Cost: $0.71 / member
Perp. connection every 9.043" OC

Frame Horizontals
Length: 10'10.08" / member
Cost: $0.73 / member

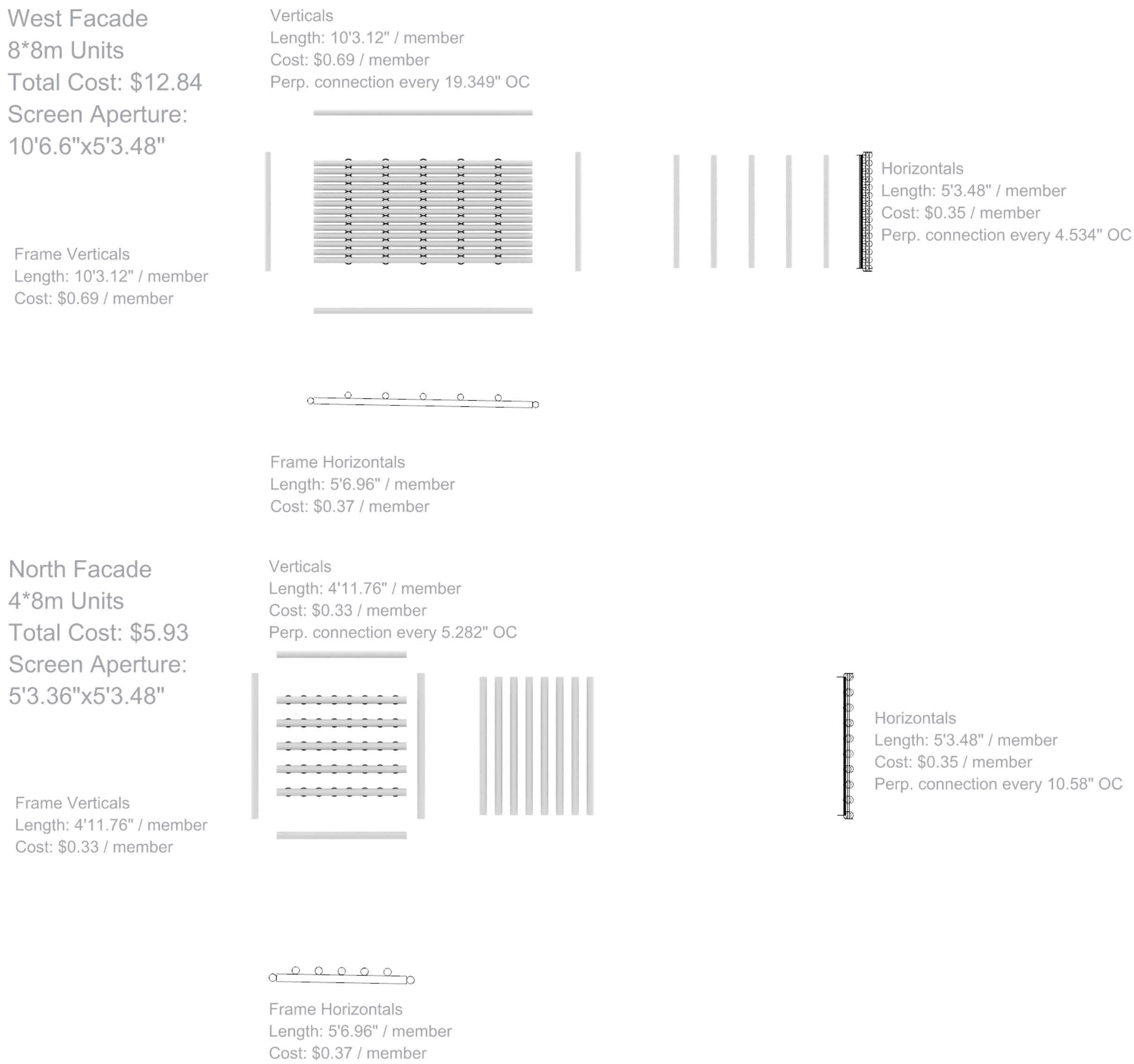


Figure 33.b Most Optimal Solution

Elite A vs to Elite B

	Radiation *kwhm2yr*	DL Illum. *lux diff.*	E.Load $ *$m2yr*	Material $ *of bamboo*	Illum. Val *lux*	Material *units*	Total Ft. *of bamboo*	Rank *external*
Elite A	[1] **13.6**	[1] **122.2**	[1] **938.08**	**56.02**	[1] **1772.24**	**43*6m**	**835’**	**4/8**
Elite B	**99.19**	**981.1**	**940.81**	[1] **45.91**	**2631.11**	[1] **27*8m**	[1] **684’**	**3/8**

Figure 33.c Most Optimal Solution

CHAPTER 5: CONCLUSION

5.1 SUMMARY OF TAKEAWAYS

Quantitative descriptions of the qualitative criteria of the applied screens are utilized in the computational model. In doing so, the solution space is constrained based on the pre-conceived expectations of the possible outcomes, also known as the objectives. Unwanted emergent properties of designs resulting from unexpected combinations of parameters are significantly reduced due to the nature of the elitist genetic algorithm utilized. Due to the subjective nature of qualitative criteria such as the visual appearance of the vernacular screen, decisions made solely on that notion tend to oversimplify the problem, discrediting and neglecting necessary factors and rendering the selected resolution ineffective to the actual goals of the required design. By this outlined process the emergent result is a combination of the combined state of many parameters of the design aligned to the 4 measures (objectives). The framework allows decision makers/designers to benefit from a process of selecting based on their intuition, preference, or expertise, their design problem resolve from solutions that are already quantitatively validated.

The generative genetic optimization script allows decision-makers to explore and analyze complex systems in a virtual environment, which helped to improve understanding and inform decision-making. For this study, the integration in the framework was successfully used to administer the prediction of behavior in conditions, optimize the performance of the system or process, reduce the time and cost associated with physical prototyping and testing, and the evaluation of the impacts of different design choices. In the end in regard to the first goal, the framework developed as a means to develop and test the most optimized screen solutions, it is hoped to be an example for other stakeholders who hope to digitize similar vernacular system solutions as a remittance to climate challenges in communities located in places with relatively similar climates as the base case. From the 2nd goal, we were able to calculate the cost of adaptation to select the most feasible system that addressed economic and environmental impacts. The results validate the viability of the framework and its outcome (*Figure 33.5, 33.6, Table.8)*.

There are multiple elite choices not just one final solution, this may not have been foreseen unless knowing the nature of the generative process of design optimization problems. In this case, the most elite choice changes depending on which percentage difference metric /objective values are considered in the comparison function; whether just objective fitness alone, attribute metric values as well, or a selection between the two. Selected and validated was Elite Solution A since its 3 applicable objective fitness values in percentage compared to the base case's values have the smallest percentage meaning it was minimized the most in this case. Additionally, the Material cost value is compared as a percentage difference to the monthly min. wage in Lagos ($65) multiplied to a 1-year minimum wage of $780. A year is selected because this is the timeline for all the other metric calculations developed from the simulations that inform the fitness objectives. The total percentage of optimization calculated for the objective values in the analysis of the vernacular configurations as they relate to the contemporary window application proves elite-A's solution to be the best.

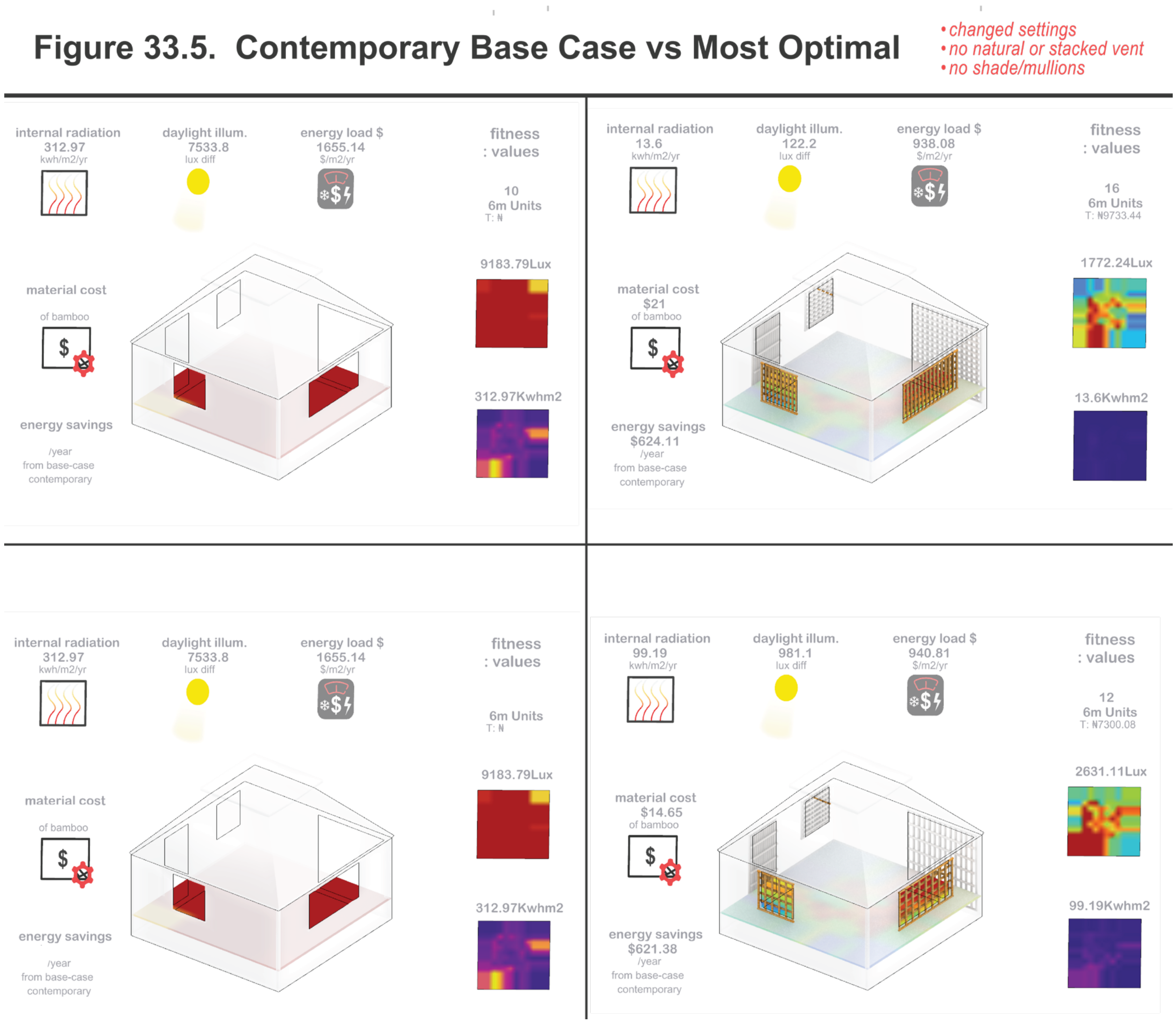


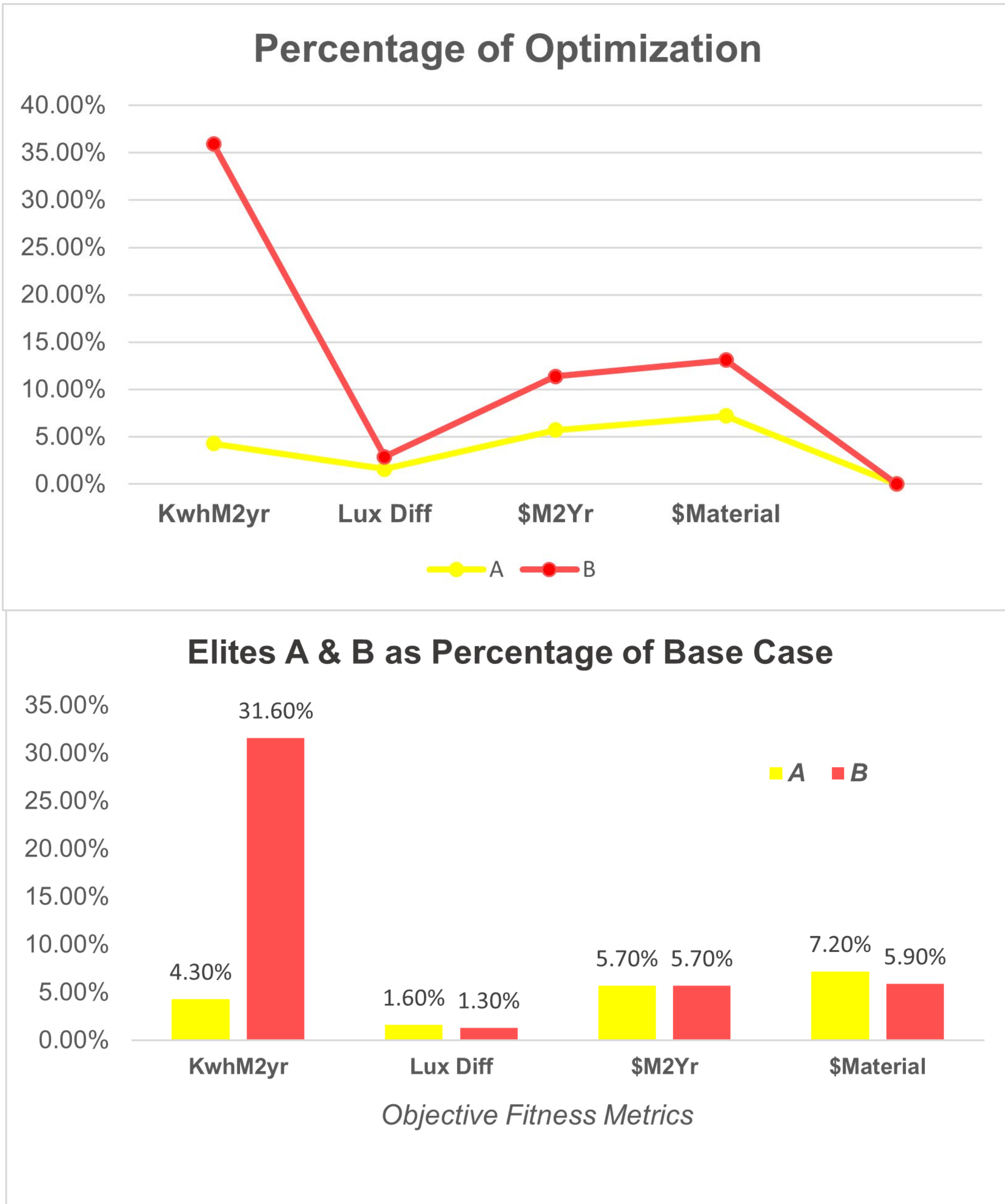
Figure 33.5 Contemporary Base Case vs Most Optimal

Table 8. Contemporary Base Case vs Most Optimal Vernacular

	Radiation *kwhm2yr*	DL Illum. *lux diff.*	E.Load $ *$m2yr*	Material $ *of bamboo*	Illum. Val *lux*	Material *units*	Total Ft. *of bamboo*	Rank *external*
Elite A *Vernacular window treatment*	1 13.6 4.3%	1 122.2 1.6%	1 938.08 5.7%	56.02 7.2%	1 1772.24	43*6m	835’	4/4 18.8%
Elite B *Vernacular window treatment*	99.19 31.6%	981.1 1.3%	940.81 5.7%	45.91 5.9%	2631.11	27*8m	684’	0/4 44.5%
Base Case *Contemporary window treatment*	312.97	7533.8	1655.14	Null $780 Min Wage/ Yr	9183.79	Null	Null	Null

rank % difference * Material % as it relates to Monthly wage in NG @ $65/ month

Figure 33.6 Optimization Validations



There were some challenges found with the consistency of the visualization scripts which had to be re-edited to function properly. There were still found discrepancies between the recorded values, although the correct values were input into the optimization. The values for cost and units on the axons for the Elite optimizations only reflect the south façade values. It could be said that there may have been more success outputting within BIM software specifically for output documentation and building information. One main challenge was determining the workflow path for optimal selection The elitist way utilizes selection from the *Octopus* interface which has to be interacted with at some point by the user, which may pose the issue of understanding, instruction would need to be included on how to select the last best options. It would have been simpler to be able to select any individual from any generation and reinstate it immediately. Both optimization selection paths are integrated as options and decided by the user based on comfortability and understanding *(Figure 28)*. A restriction to the implementation of the framework by users will be its compatibility with existing models, it is at this stage created to redevelop a particular typology of vernacular homes that can be reimplemented in similar contexts, the form and façade structure can only be selectively modified to a certain degree *(Figure 34*). Without the involvement of community organizers and governmental support the framework, if implemented in future work, would lack accessibility to use the digital service in low-income communities and developing nations. In the same way, the need for stable and reliable electricity to run the optimization efficiently posed a challenge even for this POC. If computation power was greater the solution viz script could reinstate several solutions using flow 2. The metric outputs for those solutions would be calculated in the difference percentage comparison functions and ranked by most minimized %, this could have been added to the "Optimization Comparison Axon".

Figure 34 User – Framework Relationships

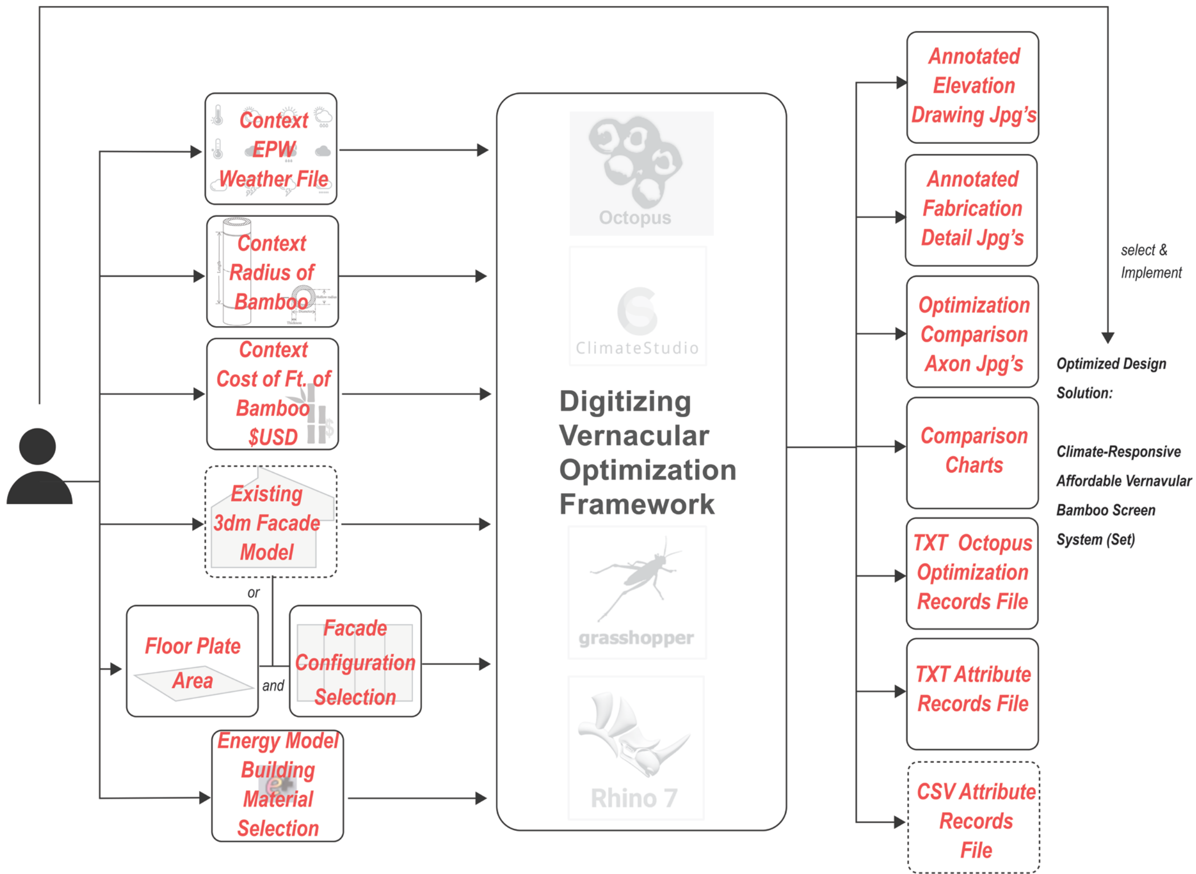


Figure.34 User-Framework Relationships

Table 9. Proof-of-Concept Indicator Evaluation

Indicator Based Evaluation of Most Optimal as Proof of Concept

Indicator *as it relates to the reasoning for the design problem: climate challenges, affordability issue of climate responsive housing*	0-5	**how it's met**	**needs further validation**
•Initial Construction Costs	5	•As captured as USD on output graphic record	• test in RW. •can find & give cost/ sq' digitally?
•Labor and Resource Requirements of Production/ fabrication	3	•Low tech build due to nature of vernacular solutions, but requires skill or trade to learn the craft. this can increase skilled labor in communities. With programming and instructional training (days or a week). •however high tech in regards to the framwork being digital and access being limited unless aided	•Requires RW fabrication and recording of process
•Modularization & flexibility	5	•Capture by screen system organization, modules of 1 that can be scale dto 8 for the facade application. the design is parametric by nature and can adapt, but is restrictive on what for(building mass) it can process currently.	"
•Economy of Scale	0	•Not sure if price reduces with the more applications of screen, with larger projects	•Needs testing digitally, RW would be expensive
•Time Schedule	4	•Time of solution of optimization framework to give design significantly less than traditional. Run occured within a day. Projected efficient fab.	•Runtime needs to be better recorded, think it took 6 hours or so
•Interface to basic utilities	3	•the configured technology can be applied to existing structures as a means to mitigate	
•Local value creation	5	•Could become a new typology, and a common ground between squatters and government entities at conflict	•validation and feasibility studies required for socially acceptability
•Resiliency/Sustainability	5	•uses naturally found resource that is recyclable & can be reused (scaffolding). also proven climate responsive	•test detail of assembly methods, nail + cord vs reusability

Table 9. Proof-of-Concept Indicator Evaluation [112].

5.2 FUTURE WORKS

Table 10. Digitizing Vernacular Bamboo Screens Framework Future Work

Improvements & Future Work	Vernacular Screen	Framework
•Test the same design problem with another Optimizer *(Tunny, or Wallacei)*	✓	✓
•Output table with comparison of values from selected solutions as record option		✓
•Cluster the script in gh for streamlining and easy application elsewhere		✓
•Create UI interface for simplification & conduct a UX/UI study		✓
•Extend logic by switching out the screen types from pre-study	✓	✓
•Expand range of optimization, by including screen type user election as an input for the Geometric Parametric model	✓	✓
•Extend compatibility of optimization framework with any form input, exisitng design or typology.	✓	✓
•Apply POC findings in Ebute Metta as co-op : *find investors & stakeholders, build program, Low tech version utilize forms - then implement inputs, or implement UI. acquire materials and fabricate test to validate optimization results and values in real world application*	✓	✓
•Resolve Visualization output errors - Axon Drawing : *issue of parametric calcula-tion in script*		✓
•Extension - Integrate with Revit: *via Rhino-Inside or CSV upload into Dynamo (vi-sual programming language/environment in Revit - data maniputalion focus over form development because it is for building information.*		✓
•In Revit additional documentation, Industry standard: *do costs & member sizes schedule take-offs sheet, proper formatting of all supplemental drawings such as elevations and details. Sheet could be used for project bidding.*		✓

Table 10. Digitizing Vernacular Bamboo Screens Framework Future Work [113]

The framework output of a climate responsive cost-effective vernacular screen could be determined by providing a non-computational stakeholder with a form to fill regarding the initial input values required from the use for the framework to be utilized for an optimization problem. The computational user could render aid to a community with surveys conducted by NGO, governmental organizations and community organizations as programmed initiative. The hope is to eventually get the framework to be the back end for a simple interactive user interface that can be opened with the click of a button. This would give the power to the user to interact directly with the framework functions as made available by portable technological devices which could be brought in by the interested parties and organizations (Figure 25, 26)

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