HIGH RISE MORPHOLOGIES: ARCHITECTURAL FORM FINDING IN A PERFORMATIVE DESIGN SEARCH SPACE OF DENSE URBAN Contexts

ABSTRACT
The research sets up a process driven framework as a generative mechanism to navigate architectural morphologies for high rises in a performative design search space of dense urban contexts. It establishes an architectural form finding process through embedded multi-objective optimisation of environmental parameters. Conceptual design processes in architecture is often devoid of performative analysis. Environmental simulation is often perceived as post design rationalisation or post design modification device, completely alienated from conceptual processes. The research proposes integrating an embedded logic of optimisation in the conceptual design process as an essential form finding mechanism driven by performance. Performance criteria include environmental factors - urban daylight, direct sunlight and solar irradiation. The intent of the method is to evolve multi-performing morphologies through novel emergent spatial formations by mapping of physical forces serving as formal logic. The process allows externalizing design operations through a computational framework and navigating an exhaustive search space with mutually non-conforming criteria, informing early design decisions with performance criteria. For a new high rise in a dense urban context Urban Daylight is maximised, Direct Sunlight is minimised and Solar Irradiation is minimised during summer and maximised during winter. It develops a dynamic evolution of form in conjunction with contrary requirements of parameter maps where eroded / accumulative volumes orchestrate through a field of densities to generate optimised form.
1.1 INTRODUCTION

"Within contemporary architectural design, a significant shift in emphasis can be detected – a move away from an architecture based on purely visual concerns towards an architecture justified by its performance. Structural, constructional, economic, and environmental and other parameters that were once secondary concerns have become primary – are now being embraced as positive inputs within the design process from the outset." — Neil Leach (Leach 2004, p. 10)

The origin of systems thinking and the rise of the computer, paved the way for two camps, which were and still are present in the sciences: a directed teleological approach and an undirected self-organising approach. With the notion of emergent and generative systems from system theory and drawing parallels between the act of designing and evolutionary processes in nature, an architectural system can be conceptualised differently. Architecture perceived as an evolutionary construct evolves in interaction with forces, both internal and external; addressing the increasing complexities of formal manifestation through performative and functional requirements. Optimization methods primarily borrowed from Evolutionary Biology and Computer Science offer an effective solution to the problem allowing multiple constraints to compete as the system evolves towards an optimum configuration. However, such evolutionary algorithms are computationally expensive. The current research proposes to remove jackets that make optimisation through evolutionary algorithms difficult and computationally expensive process through an embedded recursive optimisation process.

1.2 OPTIMIZATION IN ARCHITECTURE

Architecture can technologically be conceived as a collection of closely coupled sub-systems – envelope, internal spatial topology, structure, building services, occupancies, energy transfer systems. With each such system is associated a particular specialized engineering discipline and a related performance system. The overall emergent system that is architecture is made of the interactions between all such sub systems.

The objective of the research is to investigate Architectural Design Optimization of multiple sub systems, from formal and performative perspectives. The inherent multiplicity and ambiguity of the optimal for real world scenarios makes optimization a somewhat ambiguous process, being validated by the appropriateness of the search space. However partial optimization of specific aspects of architecture is possible and can be implemented in both physical models and digital simulations. Any optimum is only optimum within the conceptualisation of the problem space and the boundary conditions applied. The idea of the research is to develop an understanding of Optimization which will enable the decomposition of complex architectural design problems into a set of parameters and how based on the appropriateness of each parameter we can devise a method to navigate search space without evolutionary algorithms. The premise is to
develop a process by which one can improve measurable aspects of architectural design problems / projects and produce a series of testable optimal outcomes.

1.3 APPROPRIATENESS OF HIGH RISES

In an age of urbanization of the globe and globalization of the urban, more people are living in cities than ever before. 2007 marked a remarkable moment, when, 50% of the world population started living in cities, with a projected 75% by 2050 [Endless City project, Urban Age, London School of Economics]. Such unprecedented transformations have direct repercussions in architecture. Contemporary urban processes have enforced the relevance of large urban developments and high rises. Simultaneously, one of the greatest challenges facing architecture today is the quantity of information and the level of complexity. Studies predict a doubling of population with a tripling of urban growth in Developing World cities by 2030. Sloganized by Reinhard Goethert of MIT as 'building all of the urban housing of the past 6,000 years but this time in 20 years' (Goethert 2013) - demands a fundamental shift in practice and strategy. Even if the reality of the next 20 years is less than feared, the trend is clear: there is a great need for large urban projects and high rises.
1.4 RESEARCH FRAMEWORK

The early conceptual and schematic stages in a typical architectural design process are often alienated from performative parameters and its analytics. There is a significant reliance on intuition for optimising multiple objectives and the approach without doubt is error prone from a quantitative perspective. It also overlooks multiple better performing solutions within the design search space, at the same time overpasses solutions which are beyond human cognition and are unconceivable by the designer.

The primary opportunity provided by the established framework of the research allows externalizing design operations through a computational framework and navigating a much exhaustive design search space with mutually non-conforming criteria. It informs early design and formal decisions at the schematic stage with performance criteria establishing an integrated workflow for evaluative and analytical design operations. It provides a heuristic framework through recursive accumulation and recursive erosion process of form finding and embedded optimisation towards suggestive volume optimised distribution. The objective of the research is to develop a framework to generate a design space which combines multiple design objectives.

Figure 1
Research framework: flowchart.
2.1 ARCHITECTURAL FORM

“The manifest form - that which appears - is the result of a computational interaction between internal rules and external (morphogenetic) pressures that, themselves, originate in other adjacent forms (ecology). The (pre-concrete) internal rules comprise, in their activity, an embedded form, what is today clearly understood and described by the term algorithm.” — Sanford Kwinter, Far from Equilibrium: Essays on Technology and Design Culture

Architectural form is always paradoxical. It remains estranged and autonomous because it escapes the cultural categories by which it is assimilated and situated. The programs that necessitate and the materials that give body to form are also protagonists in the struggle against its self-determinacy and autonomy. With regard to the demand for it to be categorized, form is instigative and reactive; autonomy thrives on contestation. Accordingly, the formally autonomous project of architecture continually reasserts and transgresses its authoritative paradigms of argumentation and reconfiguration (Cohen 1997).

Architectural form, following Sanford Kwinter and D’Arcy Thomson’s logic, can be perceived as a result of interaction between internal and external forces. Environment always remains a key external force in formal manifestation. The research process incorporates adaptation paradigms into the architectural design process. Departing from a description of abstract relationships between design elements, adaptation to environment are used to evolve architectural form. Adaptation has been directed towards environmental behaviour, looking for shapes that harvest daylighting and reduce thermal exchanges with the external environment. Computation has a profound impact on both the perception and realisation of architectural form, space and structure. It shifts the way one perceives form, the way in which form is purposed, and the way in which form is produced. The fundamental concepts which underlie computational design theory and techniques expose form as a subsidiary component of environment, and environment as a complex web of energies in dynamic exchange of both regeneration and degeneration (Menges and Ahlquist 2011, p. 10).

2.2 FORM MAKING TO FORM FINDING

According to William Mitchell and Malcolm Mc McCullough (Mitchell and McCullough 1991) there exist two axes of representation. One axis is from analog to digital and the other from 2-D to n-D. A third axis to these two could be added which would take us from form-making to form-finding. Form making is often an intuitive process one that is inspired and refined. Form precedes analysis of program and constraints. Form finding is a process in which the framework is setup for parameters to interact; form emerges out of such interaction. It is a process of discovery and editing where there is an emergence of form through analytical processes. Extreme form-making tends to move towards sculpture rather than architecture, and a form often without function. Extreme form-finding lacks the philosophical underpinnings of architecture and spatial
experience. It almost becomes applied engineering—form exclusively determined by function. Known architectural design methodologies fall between these extremes. Although not intended for architectural criticism, it can be argued from this position that many canonical works result from design processes optimally balancing form-making and form-finding (Laiserin 2008). The earliest examples of form finding in architecture can be found in the works of Antonio Gaudi and his catenary structures, Frei Otto and his tensile structures. Interesting recent research in structural form finding is exemplified by John Oshendorf and Axel Kilian’s work at MIT (Kilian et al. 2005). We can also find interesting precedents through the work of Phillipe Morel, specifically of relevance here is the voxelised Computational Chair.

Form-making and form-finding are more rigorously defined with respect to designers’ ways of knowing. Distributed cognition posits that knowing occurs not solely as mental constructs, but is distributed in external representations such as maps, diagrams, sketches, drawings, models and so on. Thus, representations and media of representation are tools for knowing. Designers who “have a design” assert existence of both mental construct and external representation. Methodologies in which a premeditated mental construct arises first are labelled form-making. Architects and designers start the process in a premeditated approach with an intuitive design idea. The idea is then sketched or otherwise represented through media and tested against programmatic requirements, program and spatial connectivity. If representations embody a necessary component of knowing (as constituents of distributed cognition), then knowing is determined or constrained by the choice of representation Laiserin 2008).

3.1 PARAMETERS AND FORMAL LOGIC

Following D’Arcy Thomson’s logic of form through geometric laws in his seminal work On Growth and Form which negotiate external and internal forces, one can arrive at a different understanding of form. We pass quickly and easily from the mathematical concept of form in its statical aspect to form in its dynamic relations. We rise from the conception of form to an understanding of the forces which gave rise to it. Sanford Kwinter in his book Far from Equilibrium: Essays on Technology and Design Culture talks about the manifest form. According to him it is “the result of a computational interaction between internal rules and external (morphogenetic) pressures that, themselves, originate in other adjacent forms (ecology)”. With relevant deductions one can gradually move over to the parameter maps the research deals with and logically categorise them based on internal and external forces and hence logic.
3.2 EXTERNAL AND INTERNAL FORCES

Environmental parameters which are governed by physical quantities and laws of heat, light, and air include Urban Daylight/Reflected Illumination, Direct Sunlight/Direct Illumination, Solar Irradiation, and Wind. These are considered as external forces which shape the form of a building. Other external factors include the Urban Context - immediate and precinct urban morphology and the City Building Codes which lay down broader rules of formal limits. Internal logic of form on a critical analysis can be divided into three groups. The first based on Program and the other two based on Physics. Structural parameters relate to the Laws of Gravity and Newtonian Physics. Material distribution relates to physical properties of the materials chosen and subsequent load conditions. Program based logic includes programmatic distribution and further distribution of sub programs. It includes horizontal and vertical circulation, spatial connectivity between programs and core configurations.

A. EXTERNAL LOGIC OF FORM

1. ENVIRONMENT
   Daylight / Reflected Illumination, Direct Sunlight / Direct Illumination, Solar Irradiation, Wind
2. SITE/CONTEXT
   Building Code, Site, Urban Context and Morphology

B. INTERNAL LOGIC OF FORM

1. PROGRAM
   Programmatic Distribution, Spatial Connectivity, Core Configuration
2. STRUCTURE
   Structure, Tension/Compression members, Topology
3. MATERIALS
   Material Distribution, Material Properties

4.1 PARAMETERS

The different parameters used for the optimisation process are outlined below with subsequent description about each. Environmental parameters form the core of the research, with a framework being laid out for other factors to be applied as a subsequent layering process.

1. ENVIRONMENT-Daylight/Reflected Illumination, Direct Sunlight/Direct Illumination, Solar Irradiation
2. SITE/CONTEXT-Urban Context and Morphology
3. PROGRAM- Core Configuration
4. STRUCTURE- Structure and Cantilevered Conditions
Environmental Parameters form the core of the research for form finding algorithm. They are fed with urban context morphology which works in tandem with sun movement to generate suggestive volumes. It is the combination of the linearity of illumination (light moves in straight lines) and non-linearity of irradiation (infrared heating of air both inside and outside the envelope is complex and non-linear) that demands such modelling and form/performance finding. Environmental parameters include:

1. Urban Daylight / Reflected Illumination
2. Direct Sunlight / Direct Illumination
3. Solar Irradiation

4.2 STRUCTURE AND CORE

Core configuration and Structural parameters are highly critical for high rise design. These elements dictate many constraints for high rises. They have been proposed as parallel secondary layering process for high performing environmental morphologies. The voxelised colonies are analysed for vertical continuity to layout possible core configurations. Similarly they are tested for structural efficiency and cantilevered conditions. The combinatory hybridised form is used for structural and topology optimisation. Cantilevered conditions are the first series of filters applied. Maximum cantilever with respect to the immediate lower floor to be decided based on unit grid. It is a filtration mechanism integrated with the algorithm. Topology Optimisation redistributes volume based on loading conditions. Series of experiments were performed using different loading forces (horizontal - wind forces, vertical load after every 5 floors - self weight and dead load) and different target density and target volume values. Deflection under each condition is analysed to figure out weak points and direction of bending.

4.3 INTER-RELATIONSHIP – ENVIRONMENTAL PARAMETERS

To understand the broader relationship (direct and inverse proportionality) between the parameters we develop 2 systems of a wall with a single differently sized window opening. In a process of deploying a collection of windows into a façade, following properties are considered:

1. Urban Daylight (the more daylight the better)
2. Direct Sunlight (the less direct sunlight the better)
3. Solar Irradiation (the less heating due to solar radiation the better)

The three properties are D, S, and E respectively. A decrease in window area will result both in less direct sunlight, less solar energy. Whereas an increase in window area will result in more daylight and more solar energy. Basically we have three forces pulling the solution in different directions. The most straightforward Fitness Function we could
create for a system, where the sign in front of each variable coheres with whether we want to maximize or minimize that particular variable, looks like:

\[ F = D - S - E \]

4.4 URBAN DAYLIGHT / REFLECTED ILLUMINATION

Daylight is the part of the electromagnetic spectrum that lies between 380 nm and 780 nm. Daylight is the combination of all direct and indirect sunlight outdoors during the daytime. Urban Daylight / Reflected Illumination as used in the research includes reflected light from Earth and terrestrial objects. Directionality of light based on location and the movement of the sun, the morphology and materiality of immediate urban context and subsequent reflections on surrounding context determines the daylight conditions at any particular level of the site.

Daylight regulation is the most crucial issue not only as an energy efficiency strategy but also for its relevance to architectural design and the resulting effects on the occupants' comfort. This is corroborated by extensive research that has identified that daylight has an impact on how space is perceived. This is particularly true for workplace buildings (Galasiu and Veitch 2006), and it can contribute to well-being and productivity (Cuttle 2002; Castorina 2012).

Improving energy efficiency and reducing consumptions by the use of daylighting can prove to be troublesome due to the many and often contrasting performance parameters. An example of this difficulty is that despite increased daylight being beneficial in reducing the need for artificial lighting and subsequently increasing electricity savings, it may also increase the indoor temperature when trapped inside a space. This effect may be desired during the winter season but is likely to be undesirable during the summer when cooling loads need to be limited. Moreover, glare caused by excessive illuminance levels can be detrimental for visual comfort. It is this delicate balance between quantitative performance and geometric variables that calls for an integrated optimisation strategy that aims to widen the range of possible solutions and subsequently provide a valuable design decision support system (Castorina 2012).

4.5 DIRECT SUNLIGHT / DIRECT ILLUMINATION

Direct Sunlight is the component of daylight which is not reflected. It occurs when unobstructed rays from the sun falls on a surface. The lux levels for direct sunlight are much higher than ambient / diffused light. They are mostly not suitable for performing indoor tasks. In the Northern Hemisphere the South light has direct sunlight, whereas in the Southern Hemisphere the northern light has direct sunlight.

Due to its high intensity it should be cut off by using shading devices. Direct sunlight also causes glare due to excessive illuminance levels. It can be detrimental for visual
comfort and inhibit the correct performance of various tasks undertaken within the space. The easiest way to figure out whether a point has direct sunlight is to determine the sun vector originating from that point during the specific hour of the day. A backward ray is traced from the sun vector of an infinite dimension. If it does not have any obstruction the point is said to be in direct sunlight. The process is stopped after the first obstruction (single bounce). The first obstruction determines the point does not receive direct sunlight at that hour.

### 4.6 SOLAR IRRADIATION

Solar Irradiation / Solar Insolation is a measure of solar radiation energy received on a given surface area and recorded during a given time. It is expressed as “hourly irradiation” if recorded during an hour or “daily irradiation” if recorded during a day.

The analysis as incorporated in DIVA uses a method described by Robinson and Stone (Robinson and Stone 2004) which harnesses a Radiance module called GenCumulativeSky to create a continuous cumulative sky radiance distribution. This cumulative sky is then used in a Radiance backwards ray-trace simulation. Compared to other approaches which use hourly calculations, this approach is significantly faster with a minimal sacrifice in accuracy (Reinhart 2009). Climate-specific annual surface irradiation at node locations is used as the simulation method for deriving performative parameter maps. This is a powerful tool that can be used on an urban or building scale to identify areas in need of shading due to excessive solar exposure or locations with solar energy conversion potential. The research utilizes such node based value maps as a determinant in accumulative or erosive form finding process in turn reducing the thermal solar exposure. For summer months the less heating due to solar radiation the better it is. During winter months the more heating due to solar irradiation the better it is.

**Objective:**
- Minimise Solar Irradiation—summer months
- Maximise Solar Irradiation—winter months
- Identify areas in need of shading
- Identify locations for solar energy conversion potential

### 4.7 URBAN CONTEXT

Context is not any given intervention but the critical definition of a field of forces through which a space is produced and activated. If context actively deforms space than what are the consequences for form? The scale of the context is of critical importance not only from a performative perspective but also from a cultural viewpoint. The morphology of the urban context as demonstrated through the research act as primary geometries of interaction serving as physical external forces to shape the built form. The processes deployed include a recursive erosion and accumulation and shadow wedge intersection
calculation of the context morphology. It is important to note here that the morphologies generated are greatly influenced by the urban context, however the validity of the process holds true for a barren context, where the direction would be towards generating self-shading morphologies.

5.1 PROCESS

The logic of generating optimised voxel colonies is through an embedded optimisation process to maximise or minimise parameter maps. The main processes involved include Recursive Accumulation, Recursive Erosion and Shadow Wedge and Point Cloud Intersection Algorithm. Based on the particular Environmental Parameter a relevant and appropriate method is applied to generate optimised voxel colonies which are later merged through a weighted distribution system.

Figure 3
A. Embedded environmental optimisation; B. Solar irradiation, recursive voxel accumulation; Direct sunlight, shadow wedge and point cloud ray trace.
5.2 STACKED LAYERING AND RECURRENCE

Stacked Layering
The site plane is divided into a uniform square grid, and the site volume is divided into a uniform cubic grid. Simulation is run at the ground plane using point grid above the plane. The nodal value of simulation results are sorted to arrange in either ascending or descending order based on whether the parameter map has to be maximised or minimised. Voxels are deployed based on a maximum ground coverage. Progressively the process is repeated for each voxel layer in the z direction and consecutively voxels are deployed with the same logic. The process is repeated until we reach the maximum height.

Recursion
Following the same stacking logic, recursion is an improvement from the first process. The process is more accurate as it accounts for the effect of voxels at a higher level on all void locations lying lower. In the recursive process, as we progressively move upwards at each level, simulation is run for all void voxels in the lower levels taking into account the effect of voxels deployed on voxel space lying below.

5.3 RECURSIVE ACCUMULATION

In the accumulation process, when applied for optimised solar irradiation form generation, we start with a site plane. It is divided into a uniform square grid, simulation is run at the ground plane. The nodal value of simulation results are sorted based on whether the parameter map has to be maximised or minimised. Voxels are deployed based on a maximum ground coverage. Progressively the process is repeated for each voxel layer in the z direction and consecutively voxels are deployed. Simulation is run for the whole system taking into account the effect of voxels deployed.
5.4 RECURSIVE EROSION

Urban Daylight - Recursive Erosion

In the erosion process, when applied for optimised urban daylight form generation, we start with a solid voxel volume and we gradually remove voxels based on performance. The solid voxel volume is translated into its equivalent floor plate system each of which is subdivided into pixels corresponding to the voxels right above it. At each iteration illuminance levels at nodes located on each pixel of the floor plate are simulated. Based on the values pixels are removed following 2 rules:

1. All pixels on all the floors achieve certain illuminance and hence daylight above a certain threshold.
2. Peripheral pixels with higher values are retained and the ones with lower values are eroded.

5.5 SHADOW WEDGE AND POINT CLOUD INTERSECTION

The objective for the process is model volume distribution of mass in an empty site located within a dense urban neighbourhood based on shadows cast by the surrounding buildings.

Context Input and Point Cloud Model

An urban neighbourhood populated with high rise buildings is modelled in Rhino. An empty patch of land is earmarked in the centre of this neighbourhood. A three-dimensional point grid is overlaid within the context of the empty site. This grid spans the extent of the site boundaries on the horizontal plane and intended maximum height of the built volume in the vertical plane. The coordinates of this point grid and the surrounding buildings are exported to be used as inputs in the Daysim engine.

Shadow Wedge Calculations

The reverse ray trace algorithm used in the Daysim Engine for calculating illuminance at specified coordinates is slightly altered to compute whether or not a particular node in the input point cloud is in shadow region or not at a specified hour in the year. This process is repeated for every hour in the whole year and a database of values is generated from within Daysim.

Data Parsing and Volume Generation

The above generated dataset is then parsed using Python and an output text file is generated that shows for each node in the point grid, the number of hours in a year that the node lies within shadow region. This text file is then read inside Grasshopper and voxels corresponding to each node are placed based on user based choices (whether to generate a shadow heavy volume or sunlight heavy volume).
Process of Operation

- Solar Irradiation Optimised Voxel Colony — Recursive Accumulation
- Urban Daylight Optimised Voxel Colony — Recursive Erosion
- Direct Sunlight Optimised Voxel Colony — Shadow Wedge and Point Cloud Intersection

5.6 OPTIMISED FORM – MONTHLY, SEASONAL, ANNUAL

Month Form: Using the process and logic explained in the previous section, Monthly Forms (Jan to Dec) for each of the parameters are generated. As shown in the matrix before, based on the climate and the city it is decided whether to maximise or minimise each parameter. The selected form is highlighted and the values associated with each form is combined to generate the annual form based on optimised monthly forms.

Seasonal Form: Similar logic can be followed for seasonal distribution by combining several months together and forming a singular form and subsequently deciding whether the parameter is maximised or minimised based on the season and climate. An Annual Form is generated by accumulating a global distribution of either maximised or minimised parameter map.
5.7 HYBRIDISED FORM / DATA MERGING

The matrix of forms generated using the embedded optimisation logic are combined to develop hybridised forms. The next step of the research is to validate the combination model used. The combination is done through a weighted distribution of the metric values at nodal locations. The metrics used for the parameter maps have values in multiple scales and units. The 3 different metrics used are scaled to a uniform distribution between 0 and 1. The highest value being 1 and the lowest being 0. Based on a system of weights on a scale of 5 the parameter forms are graded and multiplied subsequently with the uniform distribution metric.

6 CONCLUSION

The main advantage of the methodology proposed by the research is to remove jackets that make optimisation a difficult and computationally expensive process. The method does not use evolutionary algorithms, instead proposes embedded optimisation process through recursive accumulation and erosion. It also gives the designer the possibility to explore the entire parameter space interactively. It creates a framework which induces multiple parameters to follow the same language through a scaled distribution. It develops a computational framework as a mechanism to connect performative/evaluative design operations. It develops a volume distribution process as a suggestive mechanism for design and form generation. The core intent of the research was to develop computational systems to externalize the design process and creating an integrated workflow for evaluative design. Hybridised Eroded/Accumulative Volumes are generated which orchestrates through a field of densities to generate optimised form. This is a process of dynamic evolution in conjunction with contrary requirements of parameter maps. The heuristic potential of the method lies in streamlining the decision making process for designers and increasing the morphological possibilities of architectural design solutions rooted in a performative design search space. The key is in providing analytical framework as suggestive mechanisms for informed design decisions. As future next steps for the research Structure and Core critical for high rise design will be holistically incorporated. Also a system would be devised to merge Environment, Structure and Core in a streamlined, intuitive and interactive process.

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