

A tool to support sustainable neighbourhood design in contexts of uncertainty of building's geometry

A research proposal

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“Nor only is the city an object which is perceived (and perhaps enjoyed) by millions of people of widely diverse class and character, but it is the product of many builders who are constantly modifying the structure for reasons of their own. While it may be stable in general outlines for some time, it is ever changing in detail. Only partial control can be exercised over its growth and form. There is no final result, only a continuous succession of phases.”

Kevin Lynch

The Image of the city, 1960

Abstract

The present research proposal aims to develop a tool able to support sustainable neighbourhood design in contexts where high uncertainty exists regarding the 'final' geometry of buildings. This uncertainty is proper of contexts where the petty commodity form of housing production is widespread, incremental dwelling development is common and law enforcement is weak. The aim is justified on the literature review, which shows that so far two independent lines of research have been developed, building dynamics on one hand and simulation-optimization of the resource flows for sustainable urban design on the other. The literature review also shows that both lines of research are converging in such a way that currently is possible to propose an integration.

A hypothesis was posed to allow the proper functioning of the proposed tool. The hypothesis is based on the control that the urban designer could exercise on the individual developer by using constraints other than legal, in particular how street grid and plot pattern design could limit the available dwelling design options a self-builder has, so the whole neighbourhood system could be driven to better sustainability performance.

A methodology based on Shi et Al.'s (2017) workflow for simulation-based urban form generation and optimization modelling is proposed. The workflow should first serve to test the hypothesis and then serve as a base for the proposed tool. The methodology consists of three steps: Data collection, form generation and optimization. The first step will be done by a through reliable sources consultation and UAV photogrammetry. The second will use Agent-based modelling to generate building geometries based on people's behaviour simulation. The third will use an energy modelling tool coupled with Multi-objective optimization algorithms.

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1. Introduction

The nature of cities as complex self-organizing systems has been widely studied. From an urban morphology perspective, most studies have dealt with growth patterns and land-use change. At the neighbourhood scale, few studies have been done on the dynamics of building's change and evolution. In developing countries, the predominant forms of housing production, provide control to the user on the design, building and management of his dwelling. This, along with weak institutions (unable to properly enforce building regulations) and progressive building development (due to lack of immediately available capital), produces a great uncertainty when trying to forecast the resulting urban fabric at the planning stage of new urban development. Having certainty on how will the urban fabric look like when an urban project is built, is important for current tools for sustainable urban design, as it allows to evaluate the environmental impacts of a design proposal. The current research proposal works on the base that, even when dealing with contexts where uncertainty regarding the form of the urban fabric is the rule and not the exception, stakeholders should be able to access support tools capable of informing them on the environmental impacts of different neighbourhood design options.

The present document is composed of five other parts. The first one introduces background knowledge that justifies the research proposal. A second part is focused on clarifying the aim of the proposal, as well as defying the hypothesis on which a potential tool to support urban design under the given context should work. A third part will introduce the methodology, presenting a workflow to be utilized when the research is developed and justifying its election. The fourth and longest section is devoted to summarize the relevant literature review. This part consists in several sub-sections which deal with the state of the art relevant to the research, the definition of the scope of research, and a detailed review of the relevant

methods, where each of the components of the workflow presented in part three is further developed and the way they will be applied is explained. The final part presents a Gantt chart on which the work plan to develop and complete the research is presented.

2. Background/Motivation

Cities are large, complex systems (de Roo & Rauws, 2012) composed of both tangible and intangible components. Its components interact and produce “emergent” phenomena that allow structures to self-organize (Boeing, 2018). Complexity refers to the higher-order phenomena arising from the many connected, interacting subcomponents and describes both its dynamics and structure (Batty, 2005) while emergence refers to the appearance of these characteristics over time as the components self-organize (Goldstein, 1999). City dynamics can be easily perceived daily just by looking at the changing traffic flows of a busy city street. The dynamics of other urban components, such as changes in the building form on a streetscape, are harder to be perceived. This is due to the relatively longer endurance of buildings in time and their relatively slow construction processes. Although their rhythm of change is slower, buildings in a city are used and transformed constantly through time and are “considered as organisms” (Moudon, 1997, p. 3).

The focus of the current research proposal is the dynamics of these tangible urban elements at the scale of the neighbourhood. With tangible urban elements I mean those that have a physical presence on the city. These elements might be classified as part of both, the urban form and the urban fabric. The urban form refers to the shape, size, density and uses of a city (Williams, et al., 2000) while the urban fabric focuses on the physical characteristics of an urban area as it refers to the ensemble of streetscapes, buildings, landscaping, signage, lighting, roads and other infrastructure (Designing Buildings Wiki, 2019). These elements are

in constant transformation, but they do not show the same rhythm of change. Due to this, they need to be approached bearing in mind their inherent dynamic capabilities. Based on Shi & Al. (2017, p. 125) the elements of the urban fabric can be classified into six categories that go from rough and enduring to fine and ephemeral. These are site, streets, plots, buildings, programs and objects.

The elements of the urban fabric have shown to have a direct impact on the sustainability of neighbourhoods and cities as a whole. Buildings' geometries studied at an urban scale have proven effects on energy consumption (O'Brien, et al., 2010), outdoor and indoor thermal comfort (Johansson, 2006) and urban metabolism (Thomson & Newman, 2018).

A key to understanding buildings' effect on urban sustainability is to bear in mind their use. Housing is a particularly important component of the city. On average, residential land-uses occupy between 65 and 75% of the surface of a city (Rodrigue & Notteboom, 2017) and residential energy consumption (REC) is typically more than 20% of the final energy consumption in developed countries (such as France, where the share is 25%) (Dong, et al., 2018). Dwellings are also the places where people spend most of their lives and would want to feel as comfortable as possible.

Tangible urban elements are an object of interest for both, purely analytical urban morphologist and practice-based urban designers. Both types of professionals also find interesting to study the existing relationship between the urban fabric and urban sustainability. To cope with the need for studying this relationship, a series of tools have been developed to be used by both morphologists and designers. These tools include independent indicators, credit-based urban sustainability standards (such as LEED-ND, BREAM and others)

and digital tools that support the design and analysis of the urban fabric (usually implemented through specialized software such as GIS, CAD, BIM and others).

Although the dynamic of the urban fabric is self-evident, and though it is an integral component of city's behaviour as a complex system, currently existing supporting tools for sustainable urban design seem to be trapped in what Portugali (2000) called the 'first planning dilemma'. This dilemma consists in assuming that a planning procedure will "enable us to plan and implement the good city efficiently and rationally" (Portugali, 2000, p. 125) disregarding the self-organizing nature of cities. This dilemma implies that to obtain a 'good', 'adequate' or even 'sustainable' urban fabric, this should be (i) implemented in a top-down manner and (ii) kept static during its lifetime. This assumption negates the bottom-up emergent nature of cities.

The fact that existing tools to support sustainable urban design negate the emergent nature of the urban fabric is related, I suspect, to two factors. On one hand, urban design sustainability assessment tools have derived directly from its counterparts devoted to architectural design, and therefore have inherited the assumption that the designed object will be built as drawn on the paper. This is natural and desired in smaller architectural objects, but unrealistic at the urban scale. On the other hand, such tools have been mostly developed and are widely applied in advanced capitalist countries, where the industrialized form of housing production predominates. Under this form of housing production, the final product assumes a 'standardized form' (Burgess, 1978, p. 1114) so that there is little space for modifying a building during its lifetime.

Advanced capitalist countries are also characterized by having a highly institutionalized judiciary and legislative apparatuses on whom the rule of law is sustained. For urban planning

and design, this means that restrictions posed to building development are expected to be fully observed by developers. Even if the developers have full freedom to design and build their dwellings, the masterplanner would work under the certainty that an optimally-designed urban fabric will be implemented as designed. Under these conditions, studying the evolving form of buildings and assessing its sustainability, would be perceived as a useless waste of time and resources.

Although under capitalism “the industrialized form of the production of the housing commodity dominates all activities in the housing sector” (Burgess, 1978, p. 1113) in some geographical contexts it allows for the survival of the petty commodity forms of housing production. These forms, which are still dependent on the industrial one, are the manufactured and the self-help. One of their key characteristics is that they allow the user to exercise more ‘control’ on the design and construction of his dwelling (Burgess, 1978).

The petty commodity forms are kept alive as a function of low wage-levels, under-valorisation of labour, restrictions on the importation of machinery, the persistence of certain ideological values attached to the individualized housing object and from the ineluctable necessity of low-income groups for some form of shelter (Burgess, 1978). These factors are more common in developing capitalist economies, where the petty commodity forms are widespread. Many developing countries are also characterized by having weak, expensive, corrupt or inaccessible law enforcement systems, while most of their populations are unable to access the financial system. This produces massive informal urban growth, which clearly characterizes the urban form of the global south.

In Peru, it is calculated that self-built housing represents between 60% and 80% of the housing stock (Agencia Peruana de Noticias Andina, 2018) (AméricaEconomía, 2013) (RPP Noticias,

2017). While in Lima, the most populated city, about 60% of the urbanized land has informal origins (Sáez Giraldez, et al., 2010). Most of the production of these housing stock was triggered by the radical transformation that the country suffered in the second half of the 20th century when the share of urban population as part of the total went from 47% in 1960 to 73% in 2000, with an absolute increase of 14.5 million new urban dwellers (United Nations, 2018).

The way that self-built neighbourhoods were planned and developed during the most acute period of the country's urbanization, drew international attention when the British architect and housing theorist John F.C. Turner published his writings on his experience working in the country (Turner, 1976) (Turner & Fichter, 1972). At that time and place, dwellers (sometimes with state intervention) formed autonomous organizations that communally and incrementally developed the land and built dwellings. Turner "presented so vigorously Peruvian cases that the 'Turnerian vision' of urbanization, housing and community development in developing countries was, in many ways, derived from Peru" (Bromley, 2003, p. 272)

While Peru currently holds, as most Latin American countries, a predominantly urban population with decreasing fertility figures (United Nations, 2018), other regions of the world are still to experience the explosive population growth the country saw in the 20th century. Africa is the region expected to see the largest relative increase in the size of its population, going from 1.19 billion people in 2015 to 1.68 billion in 2030 (United Nations, 2015). It is also projected that it will be the region to experience the most rapid growth of its urban population, accounting 300 million new urban dwellers by 2030 in comparison to the figures of 2015 (United Nations, 2015). Although Asia's relative growth of urban population will not

be as impressive as Africa's, it will still be in absolute numbers the major contributor of new urban dwellers (United Nations, 2015). Many of the countries driving this explosive growth are present in the UN's list of developing and least developed countries (United Nations, 2019). It can be expected therefore that most of the housing to be produced in the upcoming years, will be done under the petty commodity forms.

Whilst explosive urban growth is not a new challenge, it demands creative approaches now more than ever. 'Sites and Services', a type of urban development designed to provide low-cost housing in the global south by mimicking some features of informal settlements, is an example of such a creative approach. Widely promoted by international organizations in the 70s and 80s, it aimed at reproducing positively perceived characteristics of informal urbanization (such as self-construction, progressive development and mutual-aid) in a formal context (Burgess, 1978). To pursue such aim, 'Sites and Services' was usually coupled with 'Aided Self-help', this means, an empty 'site' was provided with basic 'services' so housing could be provided via 'self-help' with external technical 'aid'. Such aid included the site planning in which an architect, in a participatory effort that included the community, would set first a programme and then a neighbourhood design to be implemented by the community via self-construction.

Mistakenly acknowledged as John F.C. Turner's main contribution to global discussions on housing policy and theory (Harris, 2003), 'Sites and Services' was abandoned in the late 80's when the neoliberal revolution gave an impulse to more 'market-oriented' policies (Fernández Maldonado, 2015). Nevertheless, this type of housing development has left a visible trail in the urban fabric of many cities in the global south and is still (limitedly) applied as an alternative for housing provision in some regions of the world.

Summarizing, the current chapter has introduced some key concepts to understand the research proposal. In doing so, it has discussed the issue of the lack of tools that support sustainable urban design and that take into account the dynamics of the urban fabric, in particular building dynamics. The issue of whether there is a real need for developing such a tool has also been tackled. Its potential development is justified on the grounds that (i) although the petty commodity form of housing production is the predominant form of housing production in the developing world, there has been little to no attention on developing tools that support the sustainable management of its highly dynamic urban fabric, and (ii) it is precisely in the developing world where most of the absolute increase in the number of urban dwellers will happen in the upcoming years, and therefore a correspondent increase in the production of housing in the petty commodity form is expected with its consequential impacts on urban sustainability.

On these grounds, the current research proposal aims to develop a simulation framework whose primordial objective is to serve as a supporting tool for sustainable urban design in contexts where uncertainty exists regarding the development of the urban fabric studied at neighbourhood scale, in particular uncertainty regarding buildings' geometries. Housing produced under the petty commodity forms make the case for such tool, not only due to the flexibility that dwellers exercise on the design and construction of their homes and their progressive development, but also due to the importance for sustainability that this form of housing production will have in the upcoming decades. A possible application of this tool would be to support the technical help provided to 'site and services' developments.

3. Aim & Hypothesis

The aim of the proposed research is to deliver a tool allowing the study of the urban fabric bearing in mind its spatial-temporal dynamics. The study of the urban fabric is justified on the grounds that it has proven effects on the sustainability of a city. The selected scale of the study is the neighbourhood, as key elements of the urban fabric affecting urban sustainability (buildings, plot patterns and street grids) can be best studied at this scale. The petty commodity form of housing production has been chosen as the preferred type of urban development to be studied, due to its characteristic spatial-temporal dynamics and its importance for future urban sustainability. As such, the tool should serve in contexts characterized by having weak, expensive, corrupt or inaccessible law enforcement systems, common in developing countries where the petty commodity forms are widespread. The main users of such tool would be urban designers who, having sustainability as an objective, could assess different urban design options for petty commodity produced housing neighbourhoods, taking in account their incremental nature. A typical example of this would be to support technical aid on 'site and services' schemes. Additionally, such tool could be useful for purely analytical urban morphologist, who may want to study possible future sustainability scenarios for existing incremental neighbourhoods.

The existence of the proposed tool is based on one hypothesis, key to develop the current research proposal. This hypothesis holds that *adequately implemented by using optimization techniques, the sum of legal (non-tangible) and physical (tangible) constraints posed to the development of dwellings produced under the petty commodity forms, are more effective in improving the sustainability performance of a neighbourhood than the application of only legal (or non-tangible) constraints.*

To understand the posed hypothesis, constraints are key concepts that need to be explained. Constraints, legal or physical, limit the possible dwelling solutions that a designer can propose on a given plot. The difference between these two is that physical constraints cannot be avoided at all, while legal ones need the rule of law (which is site-dependent) to be obeyed. The definition of physical constraints on the present proposal is greatly influenced by the logic followed by informal urbanization. There, once a dweller occupies a piece of land, its boundaries must be defined and respected by the “owner” himself and the community as a whole. The same logic holds for public spaces such as access roads. These limits originate as part of a social agreement and then become hard ‘physical’ boundaries which should not be trespassed. Other physical constraints are determined by the usability of the building as a dwelling and the universal laws of physics. The earlier determines minimum dimensions and spatial relations needed for a house to be perceived as functional, while the latter determines minimum requirements and maximum dimensions for a building to stand still and depends on the available technology.

From a top-down urban design perspective, plot boundaries and street definition are the only variables which can be controlled. What the hypothesis proposes is that, those elements of the urban design could be optimized in such a way that limit the available design solutions for individual plots, so the neighbourhood as a whole could be driven towards a more sustainable behaviour. Physical constraints will need of course to be complemented by legal ones to obtain maximum efficiency, yet the focus of the current research will be on the management of the earlier, as the aim of the proposed tool is to work within contexts where institutions are weak and laws are not fully obeyed or enforced.

4. Introduction to methodology

Self-organizing and self-governing complex systems are “two distinct sources of order in Nature, neither reducible to the other, constantly straining against one another.” (Ismael, 2011, p. 344). In both, self-governing and self-organizing systems, information and control are distributed, the difference being that, on the earlier, “there is a process that collects information distributed across the parts of the system, re-represents it, combines with stored information, and subjects it to new forms of computation.” (Ismael, 2011, p. 336). In purely self-organizing systems meanwhile, each individual makes decisions based on the immediately available information. In the end, it is the extra layer of processing that distinguishes both system types. The issue with fully self-organizing systems is that “although information about collective variables is made dynamically available to components, its bearing on components is fixed” which results in a coordinated behaviour that does not have flexibility in response function (Ismael, 2011, p. 340).

Informal urban growth is the perfect example of a purely self-organizing system. Dwellers-builders in an informal settlement make decisions on the growth of their houses based on immediately available information, without having any idea on how this might affect the overall urban system. From a sustainability perspective, the outcomes of such behaviour are contradictory. On one hand, if adequately managed, giving full control on the design, construction and management of their own homes to the users, can provide socially sustainable low-cost housing solutions (Turner & Fichter, 1972). The flexibility that such solutions provide to the user, should be able to elongate the lifetime of the house, thus contributing to environmental sustainability as well. On the other hand, a purely self-organizing urban development has very few chances of being truly sustainable, not because

individuals are against living in a sustainable community, but because they cannot be conscious of the effect of their individual decisions on the whole urban system.

Self-government can be built on a self-organizing foundation by adding an extra layer of processing, a super loop of system-wide representation (Ismael, 2011). This super loop is not able to control all the behaviour of the system but has a limited role “where flexibility of response function carries an advantage” (Ismael, 2011, p. 342). Traditionally, this extra layer of processing has been exercised by classical urban planning approaches. The communication between the processing core and the independently acting parts has been done, with different degrees of success, in the form of legal restrictions to building development.

Sustainable design “celebrates and creates the ability of communities and wider urban systems to minimize their impact on the environment, to create places that endure” (Kazimee, 2002) Computer modelling for sustainable urban design serves as a tool to inform “stakeholders so that they make well-informed decisions, knowing what the likely consequences of their decisions will be.” (Flourentzou, 2011). As such, the processing core of a self-governing urban system can take advantage of computer modelling tools to study variables hard to be analysed by using analogic means. Even more, by using optimization modelling, a computer can provide stakeholders with a selection of the most efficient solutions given an objective function, in this case, the sustainability of a settlement.

Although modelling seems to be promising in improving the efficiency of the processing core of the urban self-governing system, communication between this and the system’s independently acting parts are kept in an old-fashioned way. In contexts where institutions are weak and laws are not fully obeyed or enforced, the communication bridge between the core and the parts is partially broken so that efforts made by any modelling tool would be

unsuccessful. The current research work defends the idea that there might be other ways that could make this communication bridge, forms that directly address and cannot be ignored by the main stakeholder of the petty commodity form of housing production, the builder-dweller.

While in full control of what happens in his property, the builder-dweller does not exercise any control over what happens beyond his plot boundaries. On aided self-help projects, for example, there is a mainly top-down component in which, based on community participation, decisions about infrastructure, plot divisions and land uses are made by a team of specialists. There is also a bottom-up component, in which although having access to specialized technical support, decisions about where, when and how to build and extend a dwelling are ultimately made by the users. With minor changes, this is the logic followed by most housing produced under the manufactured form. Top-down elements pass through the same processing core that should evaluate the sustainability of a neighbourhood as a self-governing system. Could they be used as a communication bridge between the core and the independently acting parts? This question should be answered before making any effort to develop the proposed tool for sustainable urban design.

The proposed methodology aims to, (i) answer the research question by testing the posed hypothesis and (ii) serve as a base to develop a tool for sustainable urban design useful for the context of interest. For this, a workflow based on existing modelling and optimization tools should be made. This workflow should be able to:

- a) Generate building geometries based on the simulation process of progressive building at the neighbourhood scale.

- b) Measure the resources consumed and wasted by the neighbourhood during its lifetime under various scenarios. This includes the resource flows dependent on the urban fabric at the chosen spatial-temporal scale.
- c) Optimize resource flows of the system by acting on the previously defined top-down components of the neighbourhood design.

Shi & Al. (2017) proposes the idea of simulation-based urban form generation and optimization modelling. Although having a traditional approach based on the top-down imposition of the urban forms, this workflow seems to be able to comply with the required features above described by applying minor changes. The workflow consists of three steps, collection, generation and optimization. Figure 1 shows the workflow as proposed in Shi & Al. (2017), while Figure 2 shows the modified version of it to be applied in the research proposal.

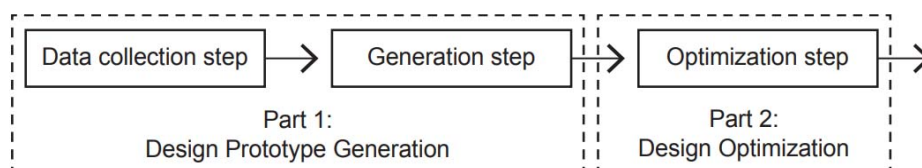


Figure 1: A general workflow of design generation and optimization modelling as shown on Shi & Al. (2017)

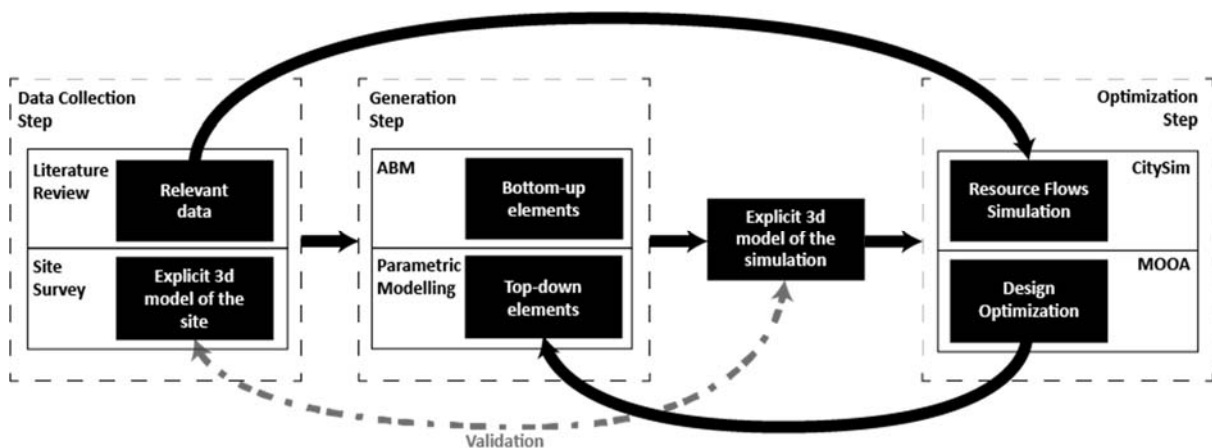


Figure 2: A detailed methodological workflow for the research proposal

The data collection step has the purpose of gathering data for the setup of the modelling tools and validation of the results. In our case, it will consist of a site survey and relevant literature review. The earlier will allow gathering spatial data for validation purposes, while the latter

will consist of reviewing reliable data sources to gather data needed for the model's setup. Regarding site surveying, the building volumes located in studied areas will be needed. For this, I propose the use of photogrammetry using Unmanned Air Vehicles (UAVs) as a reliable and cheap method.

The Generation step will use Agent-Based Modelling to generate bottom-up components of the urban fabric. The ABM will need a graphic user interface (GUI). Rhino/Grasshopper will be used as both a GUI for the ABM and a parametric modelling tool for the generation of top-down components of the urban fabric.

The optimization step needs a tool capable of simulating energy demand and district energy supply. The chosen tool, which will, in any case, have minor additions, is CitySim (Robinson, et al., 2009). Optimization itself will be done through the application of a multi-objective optimization algorithm (MOOA). To be able to bridge the optimization with the generation step, the MOOA will need to be coupled inside a CAD software with parametric capabilities. The literature review shows that Rhino/Grasshopper accounts with such integration capabilities.

To test the hypothesis, two experiments have been designed. These experiments rest upon the above-described workflow. The first experiment aims to substantiate the lack of accuracy of existing tools for sustainable neighbourhood design when they have to deal with hard-to-predict urban geometries. The second one aims to provide evidence that sustains the posed hypothesis. If the hypothesis is proven right, the second experiment should inform on the physical constraints to individual urban development that impact the most the sustainability performance of a neighbourhood.

Once, and if, the hypothesis is proven and key physical constraints are identified and correlated with their impacts on neighbourhood sustainability, a modelling tool to support sustainable urban design could be delivered. This tool will be based on the same workflow under which the experiments should be carried out. Changes will be applied on the objective functions of the MOOA to save computing time: Once identified and verified, the physical constraints driving the system towards a more sustainable performance will be directly set as objective functions, avoiding the need re-run the ABM every time a neighbourhood design needs to be assessed.

The workflow could also serve as a tool able to forecast the sustainability performance across the time of existing incremental neighbourhoods. As the aim of this second tool will be just to measure the sustainability outputs of an existing incrementally built neighbourhood, not wanting to modify its physical design, the optimization component could be discarded, being replaced by a visualization component for the outputs of the simulation tool.

5. Literature Review

5.1. State of the art

The current state of the art has found two lines of investigation which are relevant for the present project proposal. So far these lines have been differentiated and have developed in parallel. On one side there is the research interested in investigating building dynamics at the neighbourhood scale. This research is focused on understanding how buildings evolve in time and it is mainly based on the context of informal urbanisms. A second line is interested in how simulation-optimization techniques could improve the urban form for sustainability purposes. The current

section concludes reckoning that currently there is the need and the tools for both research lines to join in a point represented by the proposed research.

5.1.1. *Building Dynamics at neighbourhood scale.*

Cities complexity and its emergent nature has been widely studied. These studies are mainly referred to the expansion of the city, quite often with a focus on the informal expansion (Inkoom, et al., 2017) and on the land-use change (Chaudhuri & Clarke, 2013). Flows inside urban areas are also quite common (Kaziyeva, et al., 2018). For these studies, the most used methods are different forms of Agent-Based Models (ABMs) and Cellular Automata (CA).

Although the study of cities complex and dynamic nature has been quite extensive, the study of building's dynamics as an integral component of urban complexity is still a novel field of study, moreover, if we consider a focus on housing produced under the petty commodity form. In the present literature review, I will present four studies made on the topic of building's geometry dynamics at the neighbourhood level. These studies have been published in the last 10 years. Although some might look too old for a state of the art, they represent the universe of few publicly available studies on the topic. All of them approach the topic with a focus on self-construction under the petty commodity form of housing production.

First, I will present the continuum of Donath & Gonzalez-Böhme (2008) and Alvarado, Donath & Gonzalez-Böhme (2009), the oldest of the studies presented. These focus their research on a "site-and-services" neighbourhood developed in Chile in the 1970s and use constraint-based design theory to develop digital tools that allow them to investigate the evolution of the dwellings in the neighbourhood. Then, I will present

Augustijn-Beckers & Al. (2011), who focus their study of the evolving geometry of housing in Informal Settlements (IS) in Dar es Salaam: By using ABM as method and urban patterns studies as validation, they were capable of simulating the infilling, extension and enlargement of existing houses in the neighbourhood of Manzese. Finally, Pena-Guillen & Murakami (2017), the most recent and only example based in Peru, shows how CA can be used to simulate the self-built consolidation process of houses in an urban block in the semi-peripheral neighbourhood of Chillón in Lima.

Donath & Gonzalez-Böhme (2008) deals with the building massing design problem posed by the Chilean urban regulatory framework addressing single-family affordable houses. The paper aimed to open the discussion on the requirements and effect of the computer implementation of a constraint satisfaction approach to solving elementary design problems in architectural practice. For this, two different implementation criteria were tested. Prototype No. 2, developed with ILOG's OPL STUDIO constraint programming environment proved to be qualitatively superior compared to prototype No. 1, implemented in CINEMA4D. Computational methods tested on prototype No. 2, proved relevant in applying constraint-based design theory and practice to participatory design practices. A side experiment focused on the programming of topological constraints to explore space allocation alternatives given the zoning lot imposed by "site-and-services" urban development was presented. For this, Prototype No. 2 was used, proving great intuition from the household members to preview the real enlargement possibilities resulting from the combination of a set of imposed initial conditions and their design constraints.

Alvarado, Donath & Gonzalez-Böhme (2009) goes further on the base set by the previous study by exposing the “site-and-services” neighbourhood in Chile as a reconstructive case study on spontaneous growth patterns underlying an unassisted, incremental self-build housing dynamics. Based on a sample of fifteen households of the studied neighbourhood, semi-structured interviews and building surveys were combined to reconstruct the sequence of states of each housing process. This was complemented by an exploration of alternative states by using constraint programming methods (Prototype No. 2 in the previous study) and spatial qualitative reasoning. Their procedure demonstrated a core technique of a computer-based planning system to support user participation in the design of incremental housing units, adapted to certain social and regulatory contexts.

Augustijn-Beckers & Al. (2011) present a vector-based, micro-scale housing model to simulate the growth of informal settlements based on ABM. This model was developed by using three simple rules of spatial change (infilling, extension and enlargement of existing houses) and two types of agents whose goal is to live in a suitable home (the homeowner and the renter). The environment in the model consists of spatially-explicit, vector-based layers of houses (polygons), roads and footpaths (lines), elevation (zones based on contour lines) and swamp areas (polygons). Only houses are captured in a dynamic layer, while the rest remain in a static one. The model was validated through the analyses of the historical growth of Manzese informal settlement in Dar es Salaam. Pattern comparison resulting from the various simulation runs showed consistency with the observed in empirical data. The research showed the feasibility of a vector-based housing simulation model. This is described as a promising tool to improve the understanding of informal settlement

growth. Nevertheless, two unrealistic assumptions were made to develop the model. First, once installed on their dwellings, agents do not move again, and second, there is no mechanism for selling houses. The model can be applied beyond Informal settlement study, as features such as building next to an existing house, building detached houses and enlargement of existing houses are generic and can be adjusted to different settlement types, although the model assumes the freedom of the owner to settle anywhere as one of its guiding principles, so it cannot be applied in contexts where the settlement is steered by a planning process.

Pena-Guillen & Murakami (2017) identifies, describes and simulates the process of house consolidation in a self-built neighbourhood in Lima, Peru. It does so by using a CA model based on actual data at the scale of the block. This research addresses the spatial and temporal dimensions of urban growth at the level of houses, fitted into the boundary of a residential block. For this high-resolution imagery was used for data retrieval. The decision of individual households to improve their houses is hypothesized to respond to interactions with close distance neighbours and resembles observed characteristics at the block scale. The model is said to be applicable under conditions of decentralized self-building decision-making, and non-restrictive building regulations at house scale. In the experiment, the model showed a non-significant degree of predictability, which was said to be due to the small number of invariant houses and a random allocation component of the update rule. Authors recommend that further work should include a more explicit representation of the dynamics of the social dimension within the space of the block.

The literature review showed few existing examples regarding the time dynamics of buildings' geometry at the neighbourhood scale. The lack of much-published work on the topic of interest might be since the petty commodity form of housing production is proper of less developed countries, where funding for research and publication of results is limited. The few case studies presented are all based in the global south, which could be seen as evidence of this hypothesis. Although few, these investigations gave a strong input to the present research proposal. Donath & Gonzalez-Böhme (2008) and Alvarado, Donath & Gonzalez-Böhme (2009) brought the idea of using constraint-based design as the theoretical foundation to pose the main hypotheses of the proposal. Augustijn-Beckers & Al. (2011) show that it is possible to use an ABM to simulate people's decisions regarding their dwellings' location and eventual expansion. It also brought the idea of working in two layers, one dynamic where the buildings are, and a static one where all the other elements of the urban fabric lay. Finally, Pena-Guillen & Murakami (2017) is the most recent and the only one whose case study is located in Peru (as the present research proposal). Although the simulation method (CA) and the hypothesised driver of the "consolidation process" (the effect of neighbouring buildings on one owns decision to build) seem weak for the current research proposal, the fact that this example deals with a situation so similar makes it a direct antecedent for the current proposal.

The main drawback found on the examples is that only Donath & Gonzalez-Böhme (2008) partially deal with the three spatial dimensions of the evolution of the building's geometry. It does so on its proposed prototype No. 1, integrated on Cinema 4d software. Nevertheless, on its conclusions, the said paper discards using prototype No. 1 in the future due to its several weaknesses, preferring prototype No. 2, used to

develop Alvarado, Donath & Gonzalez-Böhme (2009). As shown in Figure 2, for the proposed methodology an explicit three-dimensional representation is key to bridge parts 2 and 3 of the workflow. No assessment and therefore no optimization can be done without buildings height. It is understood that none of the examples presented aimed at evaluating nor improving the sustainability of the studied urban morphologies, they just aimed at simulating its dynamics. In this sense is understood that they did not consider explicit three-dimensional representations as key to their research.

5.1.2. *Simulation-optimization of resource flows at neighbourhood scale*

In common with the metabolism of human beings, cities import products for its consumption and export waste products (Robinson, 2011). Efforts to improve the efficiency of these resource flows have been approached from different perspectives. Computer modelling has been a most welcomed development, which has allowed urban planners and designers to foresee and improve the efficiency of the metabolism of existing and future urban settlements. For urban modellers, developing an all-encompassing model that considers all the resource flows going in and out of an urban area is still a challenge to be pursued. Some approaches, such as the one done by SUNtool (Robinson, et al., 2007) have come close to meeting this objective. As such, SUNtool was conceived to assist in the design of more sustainable urban neighbourhoods based on accurate simulations of energy, water and waste flows. Although presenting some limitations, it was, at the time of its publication, the most complete basis available for urban energy optimisation.

Its successor, CitySim (Robinson, et al., 2009), a decision support tool for urban energy planners and stakeholders to minimize the net use of non-renewable energy sources and the associated emissions of greenhouse gases, has proven to be relatively fast, reliable and has the advantage of needing few input data, which makes it an ideal tool at early design stages. Initially, it accounted with five core models: the thermal Model, Radiation models, Behavioural models and Plant and equipment models (Robinson, et al., 2009). Kämpf and Robinson (2009) coupled CitySim with an evolutionary algorithm. Allegrini & al. (2013) showed how coupling CitySim with the CFD simulation engine OpenFoam can improve the accuracy of the simulated building energy demand variation. Peronato & Al. (2017) developed a graphical interface to CitySim, bundled as a plug-in for Grasshopper called GHCitySim which can be freely downloaded from its webpage at EPFL. Grasshopper is a “graphical algorithm editor” plugin for Rhinoceros, a 3D modelling tool becoming increasingly preferred by designers, architects, and students alike (Roudsari, et al., 2013). Although unlike its predecessor, it has ultimately become limited to the modelling of energy flows, all the research and development existing around CitySim’s core models show the adaptability, relevance and validity of the tool.

The Urban Modelling Interface (UMI) is an urban modelling platform to evaluate the environmental performance of neighbourhoods and cities concerning operational and embodied energy use, walkability and daylighting potential (Rakha & Reinhart, 2013). Working as a Rhinoceros plug-in (Reinhart, et al., 2013) it uses EnergyPlus, Radiance/Daysim and a series of Grasshopper and Python scripts as underlying simulation engines. The urban form for each scenario has to be specified by the user and is thus extrinsic to the model (Schüler, et al., 2018). UMI includes a sustainable

transportation module which could be potentially coupled with optimization tools, such as Galapagos in Grasshopper, to be used as a way to enhance land-use allocation in a neighbourhood (Rakha & Reinhart, 2013). UMI's capability to use Building's Life Cycle Assessment (LCA) at urban level has been used to calculate the construction, environmental and operational cost on residential projects under different design scenarios (Tran, 2019) and to evaluate the environmental impact of a Middle Eastern Residential Neighborhood (De Wolf, et al., 2017).

Similarly, other tools have been developed to work within Rhinoceros/Grasshopper to evaluate the building's impact during its lifetime. Keena et Al.'s (2018) "Clark's Crow", uses the Emergy analysis method to promote awareness on the impact of different design options in the early stages of urban design-development. Emergy is the available energy of one kind that has been used up to make a product or service (Odum, 1996). "Clark's Crow" is designed to operate as a plug-in for Grasshopper, to integrate Emergy analysis during the early stages of design rather than as an isolated analysis to be carried out later.

Grasshopper gives Rhinoceros the power to perform parametric modelling with ease. Coupled with this software, optimization tools have the power to generate optimal forms with ease. Parametric optimization in urban design is derived from its application in architectural design, where it has been widely applied (Nguyen, et al., 2014). Keough and Benjamin (2010) present an automated workflow that links parametric modelling (Catia), structural analysis through a custom-designed software (Catbot) and a multi-objective optimization engine (Mode Frontier) to compute multiple architectural design permutations and aid as a tool to evaluate those designs.

Bruno & Al. (2011) work on this base to apply it to the urban design by abstracting buildings to basic geometric primitives to study programmatic and spatial relationships in a workflow of multi-objective optimization in which many design criteria are evaluated simultaneously.

Shi, Fonseca & Schlueter (2017) proposes a model of simulation-based urban form generation and optimization modelling for energy-driven urban design in an empty site with or without a context. Its method consists of three steps: Data Collection, Generation, and Optimization. The urban form is generated with certain generative methods and constraint sets (L-system or its adapted version is said to have a higher potential for their purposes) and optimized with an energy simulation program (City Energy Analyst) coupled with a multi-objective optimization algorithm (MOOA). Although the proposed model recommends using L-systems for form generation, CA and ABM are advised as valid to be used to “generate context-sensitive urban massing in a bottom-up process” (Shi, et al., 2017, p. 123). In proposing their model, Shi, Fonseca & Schlueter (2017) also reviewed the efforts of coupling design generation software with energy simulation and heuristic optimization algorithms to create and evaluate urban designs under energy aspects.

Schüler et al. (2018) present the development and application of a methodology that employs optimization not to seek a single or few optimal plan(s) but to provide planners with a systematic overview of their decision space. By using multiparametric mixed-integer linear programming approach (mpMILP), which allows to quickly generate a multitude of plans and to include both continuous and discrete decision variables, the methodology considers the existence of different decision-makers in a

planning process. Along with the methodology, a model that incorporates multiple domains (social, environmental, form, energy, and economic) and scales (from single floors up to a neighbourhood) are presented. The model uses multiparametric optimization and presents some Novel Components including Parks (their optimal allocation, accessibility, connectivity, costs, number of beneficiaries or population density), introduces Landmark View Factor and has original approaches towards Solar Availability and Energy Networks.

Ladybug tools (Roudsari, et al., 2013) is a collection of free computer applications that support environmental design and education. It includes Ladybug, Honeybee, Butterfly, Dragonfly, and EPWMap. They work as environmental design plugins for Rhino/Grasshopper that provide a variety of 2D and 3D interactive climate graphics to support the decision-making process during early-design. Its integration with parametric tools in Grasshopper allows for almost instantaneous feedback on design modifications. It has been developed as open-source, so users customize the tool based on their needs and contribute to the source code. As it can be coupled with other Rhino/Grasshopper integrated tools, it can take its capabilities further. Coupling Ladybug with Octopus (Vierlinger, et al., 2013), another Grasshopper/Rhino plugin, will allow users to easily set up and run a multiple-objective performance form optimization to maximize the amount of solar radiation during the heating period and minimize the amount of radiation during the cooling period of the year (Roudsari, et al., 2013). This interaction along the reliance of the tools on well-recognized external modelling software such as Radiance, Daysim, EnergyPlus and OpenFoam make them one of the most powerful sets of tools for sustainable design available on the market.

The reviewed simulation-optimization modelling tools have proved the feasibility of the proposed framework. Shi & Al. (2017) in particular present a methodology that can serve as a base for the model to be developed. Some changes in the methodology should be included to integrate the urban form generation model. The proposed L-System as a form generator should be replaced by an ABM, while the energy simulation software could be replaced by CitySim, whose core models have a more holistic view on the topic. Additionally, many of the tools presented have shown how CAD tools, in particular, Rhinoceros/Grasshopper have become central to integrate different sets of applications. In this sense, seems valid to pose it as a communication platform between the models of the proposed framework.

Additionally, it has come to my attention that, although the ultimate goal keeps being to develop an all-encompassing model that considers all resource flows, this has not yet been achieved. The presented tools recognize the difficulty in achieving such goal and limit their scope to modelling certain key aspects. The one tool that, although is limitations has tried to include the most resources flows at the scale of the neighbourhood is SUNtool. Schüler et al. (2018) and the UMI include several indicators regarding urban sustainability, but many are not related to the consideration of the city as an anthropogenic ecosystem. Most of the presented tools have preferred to focus more on one of their components, most commonly the one related to energy flows. In the case of CitySim, it initially aimed at including aspects such as water consumption from appliances and the anaerobic digestion of human waste (Robinson, et al., 2009), but today it has become limited to be (one of the best) decision support tools for urban energy planning only (EPFL, 2017). The UMI's focus is also energy, although having modules for daylighting and walkability simulations, the reason for

their evaluation is mainly related to the energy and emission savings that could be potentially made (Rakha & Reinhart, 2013).

5.1.3. *Conclusions to the state of the art*

The above-presented state of the art has shown relevant developments in the fields of building's dynamics simulation and simulation-optimization of the resource flows. Nevertheless, both research lines have so far developed independently. In the current research proposal, I hold the position that the time has come to bridge both paths to widen the understanding of urbanization processes in the global south and its effects on urban sustainability. My position is based on the fact that existing CAD tools, in particular, those with integrated parametric modelling assets, allow bridging both fields by using a common language also capable of visually communicate any simulation result to non-specialized stakeholders.

CitySim and UMI have evolved naturally to be able to nowadays integrate with the Rhino/Grasshopper environment. They use this CAD software as a GUI platform while taking advantage of its other integrated tools. This seems to be the path to be followed by other similar tools. On the other hand, Donath & Gonzalez-Böhme's (2008) prototype No. 1 working on Cinema4D, is a highlight example on how this integration with CAD's modelling environment is also happening within the field of building's dynamics simulation. Optimization of the urban form is another key advancement in the research landscape that will allow making possible the proposed research. In this sense, Shi, Fonseca & Schlueter (2017) methodology can be seen as a valid base to build a simulation-optimization framework on our own.

5.2. Scope

The present section has the objective of (i) limiting the research by clarifying some key concepts and (ii) setting the types of research that will be embedded in the proposed project.

5.2.1. Key Concepts

To begin with, a complex term such as neighbourhood sustainability should be limited. In the current proposal, to approach this term I will use the theory of urban metabolism. Under such an approach, cities are compared with ecological systems, where entropy is exchanged across the system boundaries (Robinson, 2011). Bearing this in mind, a sustainable neighbourhood would be one where resource flows are optimized, this is, net internal entropy production should be reduced “through the promotion of synergetic exchanges between complementary elements of this system” (Robinson, 2011, p. 8). For this, all imported elements and exported waste products during the lifetime of the system should be measured and managed in such a way that waste products find a use inside the system boundaries, thus reducing the overall consumption of resources and the emission of waste products.

According to the advances and limitations found on the state of the art, the present proposal will limit its sustainability evaluation to the energy flows relevant at the neighbourhood scale. Additionally, bearing in mind the central role that buildings’ evolving geometry has for the aims of the research, the definition of neighbourhood sustainability will be further limited to energy flows relevant to the “dynamic” bottom-up elements of the built environment (e.g. buildings). Other energy flows, such as those that involve the transport sector would not be included, as to be fully understood they would need a city-wide analysis, out of the chosen scale of study.

It is considered that the term sustainability, on its more extended version, should include three basic pillars: Environmental, social and economic (Purvis, et al., 2019). The chosen approach has an exclusive focus on the environmental pillar, in such a way that it could be argued that the proposed research could simply limit its description as an evaluation of neighbourhood's environmental impact, taking away the term sustainability from its description. Nevertheless, the proposal will not abandon the wider term as, even if it has energy flows, and therefore the 'environment' pillar at the core of its interest, other factors need to be included as relevant data for the development of the research. These will include indicators related to dwelling affordability and decent housing provision, which will give social and economic inputs to the project.

Having cleared up a key concept such as sustainability, the questions of time and space limits for the research proposal remain open. Bearing in mind that the proposal deals with the time dimension of urban development, limiting the timeframe to be studied is vital to define its scope. As buildings' dynamics are at the centre of this work, the timeframe of interest starts when a dwelling begins to be produced under the petty commodity form and ends when this building is demolished. This means that any simulation effort should be designed to start once the builder-dweller takes possession of a given plot of land (disregarding how the land was produced or obtained) and starts building his house, and should finish when the building has fully lost its use-value or when its exchange-value is below the exchange-value of the land where it sits, so its demolition becomes a question of time (unless some sort of protection is given to it of course). As not all buildings in a neighbourhood will evolve simultaneously, a threshold would need to exist to stop such simulation. This could be

defined by the time when most buildings existing in the neighbourhood are ready to be demolished.

Finally, the research needs to be based on a real-world scenario, a case study has to be defined. Peru was chosen as the country on which the model will base. Two reasons support this choice. First, a developing country with a strong presence of petty commodity housing production was needed as a case study to develop the project. As referred before, in Peru self-built housing represents between 60% and 80% of the housing stock (Agencia Peruana de Noticias Andina, 2018) (RPP Noticias, 2017) (AméricaEconomía, 2013). While in Lima, the most populated city, about 60% of the urbanized land has informal origins (Sáez Giraldez, et al., 2010). Second, there is the reported impact that the Peruvian case had on Turner's vision on housing and community development (Bromley, 2003) which evidences the particular characteristics of the country and give abundant literature about the historical development of many still existing neighbourhoods. This last point also points towards choosing a particular city in Peru. Arequipa was the first place Turner visited in the country in 1957, he worked there for some years after a destructive earthquake triggered the need for adequate housing to alarming levels, and he got his first reflections about Peru from there (Kozak, 2016). Arequipa is also the place where I am from, and where institutional networks have been already set, so the data gathering work will be facilitated.

What a neighbourhood means varies across regions of the world. In Peru, where the case studied will be, the Ministry of Housing (Dirección Nacional de Urbanismo, 2012) calculated that the nationwide average size of a peri-urban neighbourhood was about

282 individual plots. Based on this, in the current research proposal, a neighbourhood is defined as an urban area physically integrated with the city, where inhabitants have a shared sense of belonging, and whose size goes between 250 to 300 individual plots.

5.2.2. Research Scope

So far the literature review has shown the advances and limitations that relevant research has had. It has also served as a way to define the limitations that the current research could face. It has been found that, regarding the research on building dynamics modelling in contexts of uncertainty, research has reached exploratory (Pena-Guillen & Murakami, 2017) and descriptive (Donath & Böhme, 2008) levels. Although some published studies are older than a decade, that has not been a synonym of a constant and continued research development. This, as said before, might be since the phenomena studied are not common or even understood in advanced capitalist countries, where most published research comes from and where the industrialized form of housing production predominates. Meanwhile, existing research on simulation-optimization tools for sustainable urban design is well advanced, as the investigation is based on explanatory research regarding the impacts of human behaviour on energy consumption.

The present study aims to start at the correlational level. It aims to correlate the optimization of tangible constraints applicable to bottom-up and progressive individual dwelling development, with the improvement in the sustainability performance of a neighbourhood. It will also reach the explanatory level if the main hypothesis is proven right, in which case a relation of causality might be established between providing physical constraints via optimization methods and an

improvement in the sustainability performance of the neighbourhood. This relationship will, of course, need an explanation before being implemented on a modelling tool.

5.3. Detailed review of relevant methods

As Indicated before, the current methodology aims to first, prove the hypothesis that *adequately implemented by using optimization techniques, the sum of legal (non-tangible) and physical (tangible) constraints posed to the development of dwellings produced under the petty commodity form, are more effective in improving the sustainability performance of a neighbourhood than the application of only legal (or non-tangible) constraints.* Once proved, this hypothesis and the methodology presented, should serve as a base to develop a tool to support sustainable urban design in contexts of low predictability of the final urban form, proper of countries where the petty commodity form of housing production is widespread and law enforcement is weak. Land development under a 'Sites-and-services' scheme, is a good example of applicability for such tool.

In the present proposal, neighbourhood sustainability will refer to energy and related flows going in and out of a neighbourhood. These include consumed energy, waste materials produced due to energy generation for neighbourhood's consumption and the potentially produced energy from raw materials present in and produced by the neighbourhood. A neighbourhood is defined as an urban area physically integrated with the city, mainly composed of housing (above 75% of the land use), where inhabitants have a shared sense of belonging, and whose size goes between 250 to 300 individual plots. The petty commodity form of housing production is a term taken from Burgess' (1978) classification of the forms of housing production co-existing under capitalism. The petty commodity form includes the

self-built and the manufactured forms, which opposed to the industrialized one, offer wider capabilities to the dweller to personalize its design. In contexts with low access to finance, it is usual that such forms of production entail an incremental component, this is, the dwelling is built in parts according to the availability of disposable income. Constraints refer to the limits that the dweller faces when seeking to personalize the design of its dwelling. These are tangible, referring to those that allow the physical existence and functioning of the building, and intangible, those allowing the legal one. The earlier cannot be avoided at all, the latter needs enforcement to be obeyed. In most developing capitalist countries, the prevalent presence of the petty commodity form of housing production coexists with weak institutions and widespread corruption, which generates boundless development of informal housing. Optimization refers to a type of mathematical model that attempts to optimize an *objective function* without violating resource constraints. Optimization modelling has been successfully used as a method of minimum energy benchmarking for a new urban developments.

The posed hypothesis aims to find a correlation between the application of two types of constraints, which limit the 'freedom to build' exercised by the dwellers-builders, and the sustainability performance of a neighbourhood where housing is built incrementally. To do so, indicators measuring each of the variables are determined in Table 1.

Neighbourhood Sustainability	Legal Constraints	Physical constraints	Additional indicators
Energy consumed due to the production (construction) of the neighbourhood (kWh)	Floor area ratio (FAR)	Plot size (m ²)	Energy costs incurred during the construction, operation and demolition of the neighbourhood (USD)
Energy consumed due to neighbourhood's usual operation (kWh)	Maximum number of floors (n)	Plot proportions (length x width)	
Energy consumed due to the demolition and disposal of part or all the components of the neighbourhood (kWh)	Maximum permissible coverage on ground floor (% of the area of the plot)	Plot Orientation (degrees from north)	Cost of Infrastructure for alternative energy production (USD)
Waste produced by the neighbourhood potentially usable for thermal conversion into energy (Kg)	Setbacks (frontal, lateral, posterior, at ground level and at upper levels) (m)	Plot shape	Land consumed per capita (people/m ²)
Waste produced by the neighbourhood potentially usable for biological conversion into energy (Kg)	Window to wall ratios	Sides of the plot with street access (n)	
Potential production of energy from waste produced by the neighbourhood (kWh)	Minimum legal dimensions for internal spaces and internal circulations (m, m ²)	Block size and proportions (plots per block, plots per side of block)	
Potential production of energy from solar collectors installed inside the neighbourhood (kWh)	Minimum requirements for adequate natural space illumination and ventilation. (m, m ²)	Minimum Area of spaces to be functional (m ²)	
Greenhouse effect gases (GEG) emitted due to the production of energy for neighbourhood consumption (CO ₂ equivalent Kg.).		Minimum length of contact between spaces to be accessible (m)	
		Minimum length of contact between spaces and the exterior to be illuminated (m)	

Table 1: Variables and indicators relevant for the posed hypothesis

Shi & Al. (2017) proposes the idea of simulation-based urban form generation and optimization modelling. The current research proposal will be based on their workflow, which consists in three steps, a collection step, a generation step, and an optimization step. Shi & Al. (2010) proposed workflow is nevertheless based on “static” urban elements, which means that although the urban form emerges from an optimization process (with minimal intervention from a designer) it should thereafter be built on-site with minimal modifications to take advantage of the optimization process. As such it cannot be directly fitted into the present case study. As such, the reviewed methodology will be modified according to Figure 2, in page 14.

5.3.1. Data Collection and Generation Steps

In Shi & Al. (2017), Collection and generation steps conform Part 1 (so called “Design Prototype Generation”) of their workflow. The Data Collection Step “collects all physical, socio-economic data of the environment, reads the context of the site and user's customized preferences” (Shi, et al., 2017, p. 122). In the generation step, the urban form is generated with generative methods and constraint sets. Data collection will be done through the review of relevant literature where studies have been already done and data is publicly available. Additionally, to validate locally the data gathered from the literature and the model, a site survey on chosen neighbourhoods will be needed. Table 2 shows the data to be gathered by each of the methods.

Literature review	Site Survey
Disposable income for dwelling building (USD)	Real building volumes (m3)
Average Construction Costs (USD/m2)	Predominant Building materials
Average energy consumption in a household (kwh/month)	Plot Sizes, shapes and proportions
Buildings thermo-physical properties	
Commonly used HVAC systems and their costs	
Solar collector technology costs	
Energy costs	
Energy sources and their emissions	
Waste production per capita per type of waste	
Regulated maximum building volumes	
What do people understand as a minimal/finished house?*	

Table 2: Data to be gathered on step 1 of the methodology

* Due to the low probability of finding a direct answer to this question for the particular time and place studied, this method might be complemented by a survey directed to people looking to buy or build a home soon in the studied area.

A. Site Survey

Due to the lack of LiDAR data available from urban areas in Peru, photogrammetry appears as a good option to gather relevant spatial data. When coupled with Unmanned Air Vehicle (UAV) (Nex & Remondino, 2014) photogrammetry is characterized by its capability of collecting very detailed, up-to-date 3D spatial data of a small site at a relative low cost. Due to this, UAV photogrammetry has been widely used to approach informal construction both in the developing (Gevaert, et al., 2017) and developed world (Ioannidis, et al., 2009). By coupling photogrammetry data with GIS, 3D city models can be developed (Anca, et al., 2016). As such, a simplified 3D model of an urban area of interest will serve to visualize the building volumes existing in the reality. Moreover, by taking advantage of GIS capabilities, real building volumes existing on site could be contrasted with legally allowed ones, and of course with simulated ones. As such, photogrammetric site survey would serve as a data gathering tool for calibration and validation of the ABM. Additionally, photogrammetry gives information about the textures recovering building volumes, so it could be used to confirm the data gathered from literature review about predominant construction materials. Other

features of the neighbourhood, such as plot sizes and shapes, street widths, etc. can also be obtained from a urban 3d model.

To proceed with the site survey, neighbourhoods complying with certain given characteristics need to be selected as a samples. These all have to be integrated to the urban area of the city of Arequipa, Peru, will need to have between 250 to 300 individual plots, must be mainly conformed by dwellings and must have been produced under the petty commodity form of housing production. The neighbourhood must also have a widely acknowledged denomination that confirms its identity as a unity. To contrast different time slices of buildings' evolution, neighbourhoods must be in different stages of their consolidation. This will be checked by both on-site visual analysis and consultation of existing historical records. Regarding the socioeconomic level of the dwellers, neighbourhoods will be chosen taken in account census data so there is not much difference between their inhabitants. Summarizing, neighbourhoods should be similar in every aspect except on their consolidation status.

B. ABM

By reviewing the existing generative methods, Shi & Al. (Shi, et al., 2017, p. 123) conclude that "Concerning urban design, shape grammars or L-system can be used to generate building forms and layouts, road and networks and plot subdivisions in a hierarchical top-down process. On the opposite, cellular automata and agent-based modelling can be used to generate context-sensitive urban massing in a bottom-up process". This opposition; along the example given by Augustijn-Beckers & Al. (2011) where, to simulate the process of infilling, extension and enlargement of houses in an informal settlement, two layers are used (one dynamic and one static); calls for a division of the elements and methods used in the generation step. Buildings, which grow due to a bottom-up phenomena, will be generated via

the use of an ABM, while plots, buildings and street grids, which are “imposed” in a top-down manner, will use parametric methods. At the temporal and spatial scale chosen, buildings (generated by ABM) will evolve dynamically, while the rest (generated using parametric methods) should remain static. At the same time and as part of the hypothesis to be tested, static top-down elements are the ones to be optimized, while buildings should remain emerging from a self-organizing process. As a reference for the generation of the top-down components of the model, Rakha & Reinhart (2012) showcase a tool that, by utilizing terrain elevation models, was capable of generating urban forms optimized for improved walkability using genetic algorithms.

Agent-based models (ABM) are a class of computational models where many autonomous interacting agents are represented. These agents adapt and co-evolve based on the information received from the environment and each other (Elsawah, et al., 2015). Agents’ capacity of evolving, allows the emergence of unanticipated behaviours. As such, ABMs may incorporate neural networks, evolutionary algorithms or other learning techniques to allow realistic learning and adaptation (Bonabeau, 2002). To allow the programming of the agents, their goals and limitations must be clear for the modeller. Additionally if a learning technique is to be implemented, rewards for given behaviours must be defined.

In the proposal, ABM will represent the behaviour of a builder-dweller, this is, a family who is need of a house to live in but does not have access to the financial system. The simulation starts once the family takes possession of a given plot of land in a neighbourhood. How the land was produced or obtained will not be a concern of the proposed model. After being in possession of the land, the family will want to build a “complete house”. What does a “complete house” implies for the studied population will need to be found during the data

collection step. The model will assume that, apart from looking forward to live in a proper house, a family without access to the financial system will be in constant struggle for additional income to satisfy their other basic needs. Being landowners would mean that there is the opportunity to monetize this resource to increase family income. In this sense the rental of unused spaces would be a valid monetizing option. Additionally, besides the fact that their dwelling could or could be not designed by a professional, the family would want to have a minimally functional home. This implies, having spaces which are big enough to display the needed furniture and that are accessible from the outside. Donath & Gonzalez-Böhme (2008) and Alvarado & Al. (2009) serve as an example of how computer tools can predict the possible design options followed by self-builders constrained by functionality. Finally, self-builders should (theoretically) comply with legal rules ordering buildings' development.

Based on this, basic features of the ABM allowing its programming have been summarized:

- Goal: Agents have two goals. Their main goal is to build a complete house. Their secondary goal is to increase their savings.
- Constraints: These are Economic (amount of available money to perform the construction), Physical (the construction is limited to happen inside a given plot, the building must be minimally functional as a dwelling) and Legal (it should comply with building regulations).
- Rewards: If the agent has a certain behaviour we want to reinforce, a reward should be defined so he keeps behaving as such. In this case, the reward would be an increase in available money to pursue his goals. If excess area is built beyond the needs for a complete dwelling, or a part of the house is sacrificed (as long as a minimum area is kept for the owner's own housing needs), income may come due to the rental of

spaces. On the other hand, energy savings due to a change of technology for energy production or due to a change in the consumption behaviour of the agent, are traduced in money saving as well.

The ABM would need to be written using a programming language. Python is an interpreted, high-level, general-purpose programming language which currently is becoming the world's most popular coding language due to its simplicity and flexibility (The Economist, 2018). Mesa is an Apache2 licensed ABM framework in Python that allows users to quickly create ABMs using built-in core components or customized implementations; visualize them using a browser-based interface; and analyse their results using Python's data analysis tools (Mesa, 2017). GhPython is an open-source Python interpreter component for Grasshopper that allows to execute dynamic scripts of any type (Food4Rhino, 2017). These three components should theoretically allow the writing and visualization of the proposed ABM, using grasshopper/Rhino as a GUI.

To validate the ABM results, the generated urban model should be compared with the site survey data according to the different scenarios detailed in the experimental design part of the document.

5.3.2. Optimization Step

In Shi & Al. (2017), the optimization step belongs to the second part of the proposed workflow, so called "Design Optimization". To be able to perform an optimization for energy-driven urban design, "a program (or a tool) capable of both simulation for energy demand and district energy supply system simulation is required." (Shi, et al., 2017, p. 125). This tool should then be coupled with an algorithmic optimization engine, and both tools should then be connected with a parametric model of urban form generation. The use of

Rhino/Grasshopper as a GUI for the ABM will, at the same time, work as the needed parametric model. The parametric model allows to introduce core data needed for the simulation engine which at the same time provides the needed data to determine the goals for the optimization process.

A. Energy simulation

CitySim (Robinson, et al., 2009), the selected energy demand simulation engine, needs a 3d representation of the form of buildings to proceed with its modelling task. Along this data, it needs the definition of site location and associated climate data, types and age categories of the buildings to be studied and the definition of energy supply and storage systems to be modelled. To allow the generated urban environments to be read by the simulation tool, an integration of CitySim and Grasshopper is needed. GHCitySim (Peronato, et al., 2017) is a graphical interface to CitySim bundled as a plug-in for Grasshopper which could be used for our aim. The rest of the needed data would need to be entered manually after being gathered in the data collection step.

Regarding the completeness of the simulation engine for the purposes of the present research proposal, CitySim accounts with five core models: the thermal Model, Radiation models, Behavioural models and Plant and equipment models (Robinson, et al., 2009). As noted before, this will need to be coupled with other external capabilities. A waste production module similar to the one in SUNtool (Robinson, et al., 2007) can be integrated to have an estimate of the production of waste for energy production. The UMI (Rakha & Reinhart, 2013) which already integrates in Grasshopper is able to perform LCAs, bringing data about the energy use and cost during the lifecycle of the buildings. Honeybee's PV panels simulation

(Roudsari, et al., 2013) will be able to calculate the potential energy collected from the sun.

Table 3 relates the sustainability indicators with correspondent simulation engines

Tool	Indicator	Observations
UMI (Rakha and Reinhart 2013)	Energy consumed due to the production (construction) of the neighbourhood (kWh)	The tool shows LCA capabilities (Tran, 2019; De Wolf et Al., 2017).
	Energy consumed due to the demolition and disposal of part or all the components of the neighbourhood (kWh)	
CitySim (Robinson et Al. 2009)	Energy consumed due to neighbourhood's usual operation (kWh)	Relatively fast, reliable and has the advantage of needing few input data. Includes a model to simulate the behaviour users.
SUNtool (Robinson & Al., 2007)	Waste produced by the neighbourhood potentially usable for thermal conversion into energy (Kg)	The tool includes a model for refuse production. Statistical data within the region of interest is a needed input. The model did not included any differentiation between types of waste, this should be added.
	Waste produced by the neighbourhood potentially usable for biological conversion into energy (Kg)	
Honeybee's PV panels simulation (Roudsari et Al., 2013)	Potential production of energy from solar collectors installed inside the neighbourhood (kWh)	Since 2015, Honeybee includes a PV panels simulation component based on EnergyPlus.
Tools to be implemented	Greenhouse effect gases (GEG) emitted due to the production of energy for neighbourhood consumption (CO2 equivalent Kg.)	These have not been implemented yet in any model mentioned, yet their implementation is rather simple.
	Potential production of energy from waste produced by the neighbourhood (kWh)	

Table 3. Tools and indicators proposed for energy flows simulation

B. Optimization

An optimization model is a type of mathematical model that attempts to optimize (maximize or minimize) an objective function without violating resource constraints. According to Shi & Al. (Shi, et al., 2017, p. 120) "Optimization modelling is a promising method of minimum energy benchmarking for a new urban development". Optimization algorithms can be single or multi-objective. When dealing with the built environment, no single optimization algorithm can be the global "fittest". This calls for the application of multi-objective optimization algorithm (MOOA). Multi-objective algorithms find non-dominated or Pareto design solutions which, in the absence of any further information, one cannot be said to be better than the other. Due to this, the algorithm needs to find as many Pareto solutions as possible and then assess such solutions to choose only one (Martins, et al., 2014).

As shown by Roudsari et Al. (2013) one of the advantages of developing a tool inside the Grasshopper/Rhino environment is that it can potentially get benefited by the several other developments in the Grasshopper community. MOOAs inside the grasshopper environment are nowadays common. Octopus (Vierlinger, et al., 2013) is based on SPEA-2, an improved elitist multi-objective evolutionary algorithm that yields the best trade-offs between different searched objectives so the designer can choose between Pareto optimal solutions. Galapagos (Rutten, 2010), a single-objective optimization tool that can be coupled with EnergyPlus and with daylighting analysis tools, such as DIVA, utilizes GA or SA to optimize a Grasshopper model, and/or Rhino model connected to Grasshopper. Whilst this are tools integrated in the Rhino/Grasshopper environment, both CitySim and the UMI have developed their own optimization platforms (Vermeulen, et al., 2013) (Rakha & Reinhart, 2013). In any case, a MOOA needs a series of defined objective functions to be programmed. When integrating

simulation and optimization platforms, these objectives are taken from the simulation engine. Table 4 shows the potential objective functions to be applied to the optimization component. Indicators are selected due to their inherent relationship with the building’s geometry as individuals and as an ensemble.

Indicators	Objective
Energy consumed due to neighbourhood’s operation (kWh)	Minimize
Potential production of energy from solar collectors installed in the neighbourhood (kWh)	Maximize

Table 4: Proposed objective functions for a MOOA

In a final version of the tool, elements to be optimized through the generative method will be limited to the “hard” top-down elements only. To avoid the recursive simulation of building’s evolution (and the computing resources that this will require), hard elements driving an increase in the sustainability performance of the neighbourhood will need to be discovered and summarized. The experimental part should answer the following question: *How should the “physical constraints” regulating self-built dwelling development ought to be so they can be used as objective functions for a generative optimization workflow to minimize the energy consumed inside buildings while maximizing their potential for solar energy collection?*

5.3.3. Testing the Hypothesis

In order to be able to prove the hypothesis, an experiment must be carried out. In a natural set-up, making an experiment that proves the hypothesized correlation will be unfeasible. The time that dwellings take to change plus the required tools for control measurements would make a field experiment extremely long and expensive. Virtual environments on the other hand offer the possibility to recreate the behaviour of social groups and therefore simulate the emergent phenomena to be studied. Optimization modelling is better

implemented on virtual environments, on this grounds, the development of experimental design on virtual environments is justified.

Two experiments are designed to (i) prove the posed hypothesis and (ii) answer the research question opened in the previous section. This experiments are complemented by the generation of an optimal benchmark against whom results should be compared and by additional runs of the workflow for validation purposes.

A. Generating an Ideal scenario as benchmark

Given a site, Shi et Al.'s (2017) simulation-based urban form generation and optimization modelling workflow should be able to automatically generate an optimal neighbourhood design solution to be implemented. Such model should normally help an urban designer to determine its final proposal, including the local legal constraints to be applied to individual building development. The legal constraints that interest the most an urban designer are massing regulations, which directly affect building development.

Massing refers to “the built mass that occupies a site and is crucial in defining typology, scale and grain of a site” (Pitts, et al., 2013, p. 687) and its regulations exist to improve urban habitability standards by guaranteeing basic quality criteria including proper solar access, ventilation and sufficient open space (Donath & Böhme, 2008). The spread of the mass across a given area is affected by density and distribution, while in turn a certain ratio of built to open space is created (Pitts, et al., 2013). Architects and urban designers use massing as a tool to translate written regulation and programmatic needs from the paper to an early-design model. The opposite way could also be followed, which happens when the urban planner-designer uses massing as a way of foreseeing the spatial relationship that proposed rules generate on a site. In a model such as ours, buildings will be represented as “massing”

volumes, this is a volumetric representation of the maximum possible mass that buildings could lawfully occupy.

Other elements of the neighbourhood model will be optimized by having buildings' optimal behaviour as an objective. Plot shapes, orientations and proportions for example, determine to a large extent the shape, orientation and proportions of building masses that grow within them. Street grids pack plots in groups, determining corner plots and the distance between mutually facing buildings. Summarizing, the neighbourhood model obtained in this step would represent the absolute optimal design solution for the neighbourhood in terms of sustainability. As such, this model serves as a benchmark. Although optimal in terms of sustainability, this model does not answer any of the questions posed in the present research proposal. The model would show a static idealized situation, where buildings are assumed to all be built at the same time and have reached a unique level of development which would not be modified in any form. Such situation describes a neighbourhood built under the industrialized form of housing production, whilst the interest of the present project is the petty commodity form.

B. Experiment 1: Comparing the performance under presence/absence of legal constraints

In this first experiment we will find out how accurate are optimization tools fitted for the industrialized form of housing production when faced with scenarios such as those of the petty commodity form. First, let's remove the building masses from the benchmark scenario, leaving plots and streets only. These will be part of the static layer on our ABM. Inside the plots, building masses will be generated via an ABM under three different scenarios:

- Anarchy reigns. No legal constraints are obeyed by the agents when building their dwellings
- Business as usual. Based on the site survey, to agents' anarchic behaviour is capped.
- The rule of Law. People fully complies with the massing regulations.

As not all plots will be developed, nor will all the developed ones reach the maximum permitted volumes, the three proposed scenarios will differ from the idealized model. Once obtained, their sustainability performance can be compared between them and with the idealized model. This evaluation should be done at different time slices of their evolution. Theoretically, full enforcement scenario should perform as best. By comparing performances between a traditional approach, represented by the ideal model, and the novel approach used in this first experiment, I will be able to determine the usefulness of traditional approaches to the petty commodity form of housing production under different conditions of obedience to the laws. This serves as a justification for the development of the tool.

C. Experiment 2: Evaluating the sustainability performance of physical constraints in an anarchic society

Now, let's focus on the full anarchy scenario. The objective of this experiment is to understand which physical constraints will impact the most the sustainability performance of a neighbourhood. For this we will need to work under the hypothetical scenario that, after providing the builders-dwellers with their respective plots, their society suddenly became anarchic, so that urban development becomes purely self-organizational and all authoritarian institutions are abolished. The rules of capital accumulation are nevertheless kept, under this conditions the builders-dwellers start building their houses. Under those conditions, the

experiment aims to find out how could physical constraints be managed in an extreme scenario were law enforcement is inexistent.

To perform the experiment, we will need to create different urban scenarios where the way physical constraints area applied is fully controlled. These constraints include the top-down elements of the neighbourhood design (plot patterns and street grids) which can be easily controlled by using the parametric capabilities of Rhino/grasshopper. The specific parameters to be varied between models are:

1st under a rectilinear grid configuration – Streets cross perpendicularly, plots have four squared corners

- Plot size and proportions can change
- Block size and proportions can change
- Orientation can change, all plots on the same side of a block have the same orientation
- Each block has four corners

2nd under a non-rectilinear grid configuration – Streets do not necessarily cross perpendicularly, plots have different shapes

- Plot size and proportions can change
- Plot shapes can change
- Block size and proportions can change
- Orientations are multiple, not all plots in a block may have the same orientation
- Blocks may have many corners or none at all (circle shaped).

With the parametric capabilities, generating neighbourhood design scenarios under a rectilinear grid configuration should be easy and the scenarios should not be that many (27 if

we count 3 possible plot sizes, 3 possible block sizes and 3 possible orientations). Finding testable scenarios under a non-rectilinear grid configuration seems more daring. Scenarios are unlimited, and a constraint function must be found to limit the number of testable scenarios. This is a void in the present research proposal and should be solved before performing the experiment.

Once the top-down elements are generated, plots should be developed by builder-dwellers in the ABM, all acting under full anarchy. Each of the resulting models should then be evaluated and compared in terms of its sustainability performance. From this comparison, one or more of the controlled parameters should theoretically stand out as the driving force behind a better neighbourhood performance under conditions of full anarchy. At this point we might hypothesize why that or those physical constraints have an effect on neighbourhood's sustainability and why others don't, this by analysing the resulting buildings geometries.

D. Validation of the findings

To validate the findings of experiment 2, we will need to prove that the hypothetically found relationship between the presence of certain physical constraints on the development of dwellings and the increased sustainability performance of the neighbourhood will hold under different conditions. For this we set the identified characteristics of key physical constraints as goal(s) on the MOOA and generate only the top-down elements of the neighbourhood (street grids and plot patterns). Afterwards we let the ABM develop the buildings under the three scenarios defined in experiment one (anarchy reigns, business as usual and the rule of law). Their sustainability performance should be then evaluated and compared, not only between the results of this run of the tool, but also with the results obtained in experiment 1

and with the benchmark scenario. Such comparisons will allow to check the validity of the assumptions taken from experiment 2. If proven right, the physical constraints could be used as permanent objective functions in a sustainable urban design optimization tool applicable to housing neighbourhoods with highly dynamic and hard to predict building geometries.

5.4. Strengths/Weaknesses

The presented literature review has showed two lines of research relevant for the topic of study that have so far been developed in parallel. One line is interested in investigating the evolving geometries of buildings from a neighbourhood scale perspective. In developing its research it has focused on studying how this phenomena occurs in the global south. The second line is interested in studying the energy flows occurring at the neighbourhood scale. In particular it has focused on how optimization modelling can be used to increase the sustainability of neighbourhoods. Shi et Al. (2017) proposed a workflow that integrates form generation and optimization for energy conscious urban design. Based on that workflow, the present proposal has been able to suggest that the two initially identified lines of research could find a meeting point. To reach this point, a methodology is proposed. This methodology suggests simulating the progressive development of dwellings via an ABM while generating the “hard” top-down elements of the urban design via traditional parametric optimization techniques.

To be able to comply with the initial aim of providing a tool useful for urban designers operating under contexts such as the studied, the project has called for the proposition of an hypothesis. Being so central to achieve the aim, testing the posed hypothesis right is a key to develop the current research proposal. This can be assumed to be the first major weakness of the proposal.

A second weakness is the fact that, while proposing experiment 2, the literature review has not been able to find a solution to generate scenarios controlling top-down urban design components under a non-rectilinear grid configuration. Even after being able to generate them, bearing in mind the number of variables, the number of possible scenarios would be enormous. An additional effort should be done during the project development to find a solution to these matters, otherwise the key hypothesis could be tested only partially.

A third weakness is the computing time that the tool would have to take, moreover if we consider that it had to perform ABM simulations every time an urban designer needs to assess the impact of his proposal. A solution posed to this is to directly set the physical constraints identified as drivers of an improved sustainability performance, as optimization objectives. Nevertheless, the accuracy of this approach is yet to be checked.

The main strength of the proposal is its originality. By bridging two research lines that have evolved independently, the proposal could be able to deliver innovative outputs to urban sciences. Originality nevertheless has its costs, which is why the proposal could be said to be highly challenging.

6. Workplan of Completion

	Year 1											
	Oct-19	Nov-19	Dic-19	Ene-20	Feb-20	Mar-20	Abr-20	May-20	Jun-20	Jul-20	ago-20	Set-20
Confirmation Review	[Shaded]											
			Mini-Viva									
Step 1: Data Collection												
Literature review	[Shaded]											
Site Survey												
Sites selection									[Shaded]			
UAV survey												[Shaded]
Data Processing												[Shaded]
Step 2: Generation												
ABM Coding in Python												
Integrating the ABM in Rhino/Grasshopper												
Testing generation												
Step 3: Optimization												
Energy Simulation												
Integrating CitySim in Grasshopper	[Shaded]											
Develop a model for waste production			[Shaded]									
Integrating UMI's LCA on the workflow				[Shaded]								
Confirming the accuracy of the model(s)			[Shaded]									
Optimization												
Integrating existing MOOA to the workflow								[Shaded]				
Testing the interaction with the workflow										[Shaded]		
Experimentation												
Ideal scenario Generation												
Traditional approach design Generation												
Assessing the generated scenario												
Experiment 1												
Generate buildings through ABM												
Test and compare Scenarios												
Experiment 2												
Determine testable scenarios												
Generate top-down components												
ABM generation of buildings												
Test and compare Scenarios												
Validation experiments												
Thesis Writing												

	Year 2											Set-21	
	Oct-20	Nov-20	Dic-20	Ene-21	Feb-21	Mar-21	Abr-21	May-21	Jun-21	Jul-21	Ago-21		
Confirmation Review													Vacation
Step 1: Data Collection													
Literature review													
Site Survey													
Sites selection													
UAV survey													
Data Processing													
Step 2: Generation													
ABM Coding in Python													
Integrating the ABM in Rhino/Grasshopper													
Testing generation													
Step 3: Optimization													
Energy Simulation													
Integrating CitySim in Grasshopper													
Develop a model for waste production													
Integrating UMI's LCA on the workflow													
Confirming the accuracy of the model(s)													
Optimization													
Integrating existing MOOA to the workflow													
Testing the interaction with the workflow													
												Journal Paper 1	
Experimentation													
Ideal scenario Generation													
Traditional approach design Generation													
Assessing the generated scenario													
Experiment 1													
Generate buildings through ABM													
Test and compare Scenarios													
Experiment 2													
Determine testable scenarios													
Generate top-down components													
ABM generation of buildings													
Test and compare Scenarios													
Validation experiments													
												Journal Paper 2	
Thesis Writing													

	Year 3											
	Oct-21	Nov-21	Dic-21	Ene-22	Feb-22	Mar-22	Abr-22	May-22	Jun-22	Jul-22	Ago-22	Set-22
Confirmation Review												
Step 1: Data Collection												
Literature review												
Site Survey												
Sites selection												
UAV survey												
Data Processing												
Step 2: Generation												
ABM Coding in Python												
Integrating the ABM in Rhino/Grasshopper												
Testing generation												
Step 3: Optimization												
Energy Simulation												
Integrating CitySim in Grasshopper												
Develop a model for waste production												
Integrating UMI's LCA on the workflow												
Confirming the accuracy of the model(s)												
Optimization												
Integrating existing MOOA to the workflow												
Testing the interaction with the workflow												
Experimentation												
Ideal scenario Generation												
Traditional approach design Generation												
Assessing the generated scenario												
Experiment 1												
Generate buildings through ABM												
Test and compare Scenarios												
Experiment 2												
Determine testable scenarios												
Generate top-down components												
ABM generation of buildings												
Test and compare Scenarios												
Validation experiments												
Thesis Writing												



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