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Assessing the Urban Metabolism of Informal Settlements: Understanding Infrastructure Configurations and Measuring Resource Use

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“In this life, there are only two options:
Resignation or indignation.
I will never resign.”

Darcy Ribeiro

Abstract

The dynamic and increasing urbanization prospects of the global South poses several challenges for human development. Urban Metabolism methods and analyses are vastly promoted as tools to aid into understanding, quantifying and providing useful insights and outcomes. In this research Urban Metabolism scholarship and perspectives have been reviewed and considered as a whole into a discussion and development of a methodology that is designed to be applied to Informal Urban Settlements within cities of developing countries, more specific Brazil and South America. The distribution and disparities of studies and the scholarship is analysed before moving to a proposal of a mixed methods focused on a Material Flow Analysis quantification itself, mainly focused on infrastructure configurations and quantifications, in addition to resource consumption flows, such as water, energy and waste. A pilot research composed of a site visit and Participant Observations done in a field research, which supports the methodology development and its qualitative analysis is also reported. The methodology development, its findings and limitations are presented and are designed to allow future research to be done using the method to improve the body of scholarship which partially neglects that the specificities of these areas differ from the largely studied formal areas in the global North.

List of Contents

List of Figures

List of Tables

Declaration

I, Adriano Ethur Dias, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously presented for an award at this, or any other, university.

Any further publications arising from the thesis will be properly acknowledged and the same guidance taken into account.

1. Introduction

Cities are where we the majority of humans lives. In 2007 the urban population worldwide surpassed the number of rural inhabitants. Today it represents 56% of the world's population, expected to be 68% by 2050. However, the predicted rapid urbanization growth and sprawl and urban population increase in the next decades are foreseen to concentrated in a small group of countries or regions concentrated in Africa and Asia, which now holds together 90% of the world's rural population (UN-DESA, 2018).

More than half of the urban population today is living in cities with less than half a million inhabitants. Most of the world's megacities of the future will be located in major regions where developing countries are present, commonly referred to as the global South. Today, different urbanization processes are rising in the developing world in rapid pace, and, more than often, without the necessary attention from policymakers and stakeholders, leaving aside its inhabitants. Several struggles and complex problems arose leading to difficulties towards the improvement of living conditions within these regions as a whole and the promotion of a sustainable development (UNEP, 2017).

A new development perspective or paradigm arises, towards one of the pillars of cities dynamics and interactions: their resource use patterns. What can be captured in a statement by Fernandez (2014): "All cities consume resources in similar ways - and - All cities consume resources in unique ways." Therefore, it is justified, the efforts that are put into understanding key trends, patterns and to conceptualize and measure these characteristics, finding similarities and differences between cities worldwide. Urban Metabolism, which will be further detailed and discussed in this work, is a broad framework that aims to understand the city as an ecosystem, capturing, accounting and analysing its resource stocks and flows, which include, but are not limited to: magnitudes, intensities, drivers and mechanisms of interactions (UNEP, 2016; Schindler et al., 2017).

A collection of studies has helped to consolidate the urban metabolism concepts towards theory and, more recently, into practical aspects of design and planning of cities and immediate surroundings (Kennedy, 2011). Urban metabolism analysis is becoming increasingly important for the field of urban development, supporting resource management and the implementation of resource-efficient cities, specified in the UN SDG 11 (Kennedy et al., 2011, Musango et al, 2017).

However, in this process, cities of the global South have been somehow neglected (Fernandez, 2014) or stayed 'in the shadow'. Many of those considered "global" studies among the field, have barely included these regions and their proposals / conclusions often have never been put to test towards global South cities or had the few methods reproduced in other regions. A considerable existent research gap leads to a lack of approaches, knowledge and availability of reliable data in this specific part of the field. This fact undermines the enormous potential of the framework to provide necessary analyses and their outputs. These are important as both scientific and political resources, to support dealing with the increasing challenges faced in urban regions of the global South at present and future.

A key point of disconnection, where the former and present expanding rapid urbanization of the global South regions diverges from the global North development are their 'infrastructure configurations'. Global south development is more than often accompanied by problems on the provision of the most basic services to a large part of its inhabitants, including housing, infrastructure, energy, water and waste systems, as well as for employment and other intrinsic activities of a city dweller (McFarlane,

2013). Many scholars go further to argue that even the constitutions of the urban spaces of the global South are fundamentally different from the North, confronting the concepts of a 'planetary urbanization' altogether, thus, attracting attention to the necessity of a different conceptualization, focused on the unique characteristics of this Southern urbanism phenomena (Schindler, 2017). These different configurations are especially true in *informal urban settlements* (*IUS*), which usually represents the poorest and most marginalized areas within these regions and where inhabitants struggle to have access to infrastructure and its basic resources provision even when they are part of rights as citizens. The large presence of informal urban settlements around the globe, poses a challenge to improved urbanization and sustainability.

In terms of data availability informal urban settlements are also 'forgotten', or presents significant challenges to researchers which leads to an alarming data scarcity problem in areas which are in often in constant expansion and are densely populated. Another point is that when data is collected or analysed at the national or city level, often bypasses are fundamentally major differences between these areas and its more developed surrounding areas, presenting a challenge for understanding and comparisons.

Therefore, not only this major knowledge gap, to support development, exists to be fulfilled, but also the understanding of Informal Settlements metabolism and infrastructural dynamics are directly related to at least 4* of the 17 UN Sustainable Development Goals, where Equity is defined as a principle of sustainability *[*1 – No poverty; 9 – Innovation and infrastructure; 10 – Reduced inequalities; 11 Sustainable cities and communities]*.

This research aims to provide a methodology for assessing and understanding specifically how to enable an informal urban settlements metabolism resource use assessment and analysis, which is achieved through different stages. First a conceptual basis, based on literature review, including contextual observations and critiques of the existing literature and methods within the field of urban metabolism is presented. An argumentation around the usefulness of the methods is presented to discuss and provide a practical overview of how these methods could be implemented for these specific areas of cities (informal urban settlements), and if not, why these methods may be limited, incomplete or inappropriate for research within these areas.

The broad aim, which is to address the research gap that is directly related to the importance to develop a methodology which answers how an urban metabolism analysis of resource use in informal settlements can be assessed by using a combination of perspectives laid by the already existing methods and new parameters is developed through the following chapters.

The focus of the research is on infrastructure configurations and constructions materials and typologies which are now are vastly disconnected to the majority of the studies done to date focused on global North characteristics, as it is demonstrated throughout the literature review. The methodology not only aims to shed light into stocks and flows quantitative analyses adapted to informal urban settlements contexts, but also takes into account other important elements of the urban metabolism such as energy, water (provision and consumption) and waste water and solid waste management. These are also included into the discussions, reflections and steps outlined and are fundamental to the proposed approach.

Furthermore, the work is supported by a pilot research done in-situ with preliminary data collection. This analysis of viability supports the core of the methodology: a thoroughly prospective new mixed-

methods methodology that is proposed and discussed, composed by both quantitative (Material Flow Analysis) and qualitative (Participant observations and Semi-structured interviews) elements, addressing the gap represented by the urgent necessity of a bottom-up primary data collection process to enhance the understanding of the resource use within these regions. Both accountability and understanding are fundamentally explored in these steps. The methodology also relies on required 'dialogues' with local stakeholders and one of the most valuable sources of information to understand certain aspects of the urban metabolism of these areas, which are local inhabitants/dwellers themselves.

The pilot research itself is further described as a specific chapter of this work, where the in-situ observations and data collection of both primary and secondary sources are presented and discussed. The pilot research was deployed in a specific settlement in the city of Niterói, Rio de Janeiro, Brazil. In its importance and significance, it's crucial that the qualitative part of the research results from in-situ participant observations and applications of questionnaires, are thoroughly explored to support the quantitative analyses so the reality is truly understood. Limitations of the study prevented the developed methodology to be further applied in practice in future visits to the research areas.

To summarize, the research significance and importance is to contribute directly to the existing urban metabolism knowledge gaps and the body of scholarship as a whole. At the same time, it is also intrinsically strongly motivated to allow, include and expand the contributions to the support sustainable development. Not only sustainability as a whole, but to demonstrate that the present discussions are still lacking in support of the informal settlements populations that live in these rapid expanding, 'left a side', marginalized and ever-present spaces of the built environments in developing countries. To be able to find or develop ideal solutions for these problematics areas, it will be necessary to first have a thoroughly understanding of their infrastructure configurations and realities and this is what this research attempts to contribute.

The project certainly has limitations in its responses and depth of analysis that are recognized throughout the conclusions and when outlying the necessary parameters. These limitations were reinforced by the pandemic situation that the world now goes through which impeded a 2nd visit to the pilot research area which could bring further depth to the methodology compatibility and partial application of the method in practice.

To wrap up the introduction to the research, the structure of how its presented is here explicated. This first chapter gives a broad overview of the importance of the research, its aims, objectives and dialogues with the research questions to be presented.

Secondly, a literature review of the field, which starts with a focus on the urban metabolism methods usability and its critiques, moving into the presentation of the argument of the uneven distribution of the present state of the methods available in the literature and their applications. The review than advances into how infrastructure configurations of the global South differ from the global North and by narrowing it down, describes what constitutes the referred informal urban settlements. The chosen mains scope of the methodology (Material Flow Analysis) is then reviewed in further details followed by conclusions and discussions of the specific gaps to be tackled and analysed and how it does support the development of the proposed methodology.

The third chapter introduces the research aims, questions and objectives, defining the approaches used to elaborate the methodology and specifying the steps proposed. Sampling size, secondary data

sources and scaling analysis are also presented in this chapter. The core of it is composed by the specification of the Material Flow Analysis steps and the executed pilot research, composed of also a qualitative observation stage (Participant Observations) done in-situ at a specific informal urban settlement, located in Niterói – Rio de Janeiro, Brazil. The area, its characteristics and the available secondary data is described in its specific section of the chapter. The findings that support the methodology, recommendations for its applications and scope limitations are then presented.

A conclusion chapter brings together how the main aims were addressed, by reminding the reader of what the findings its value and usability, how the methodology could is a contribution to the field, its limitations and its importance for further expansion of the body of literature and policy recommendations in the field.

2. Literature Review

2.1. Urban Metabolism – From a metaphor to a framework

Cities are home to the infinite variety of activities of human life. Despite occupying only an insignificant fraction of earths land surface, less than 2%, resources overall are generally consumed by and for cities and the infrastructure that connects it, rendering cities to be responsible for more than 70% of the world's carbon emissions, although cities present fairly different levels and patterns on emissions among them (Moran et al., 2018).

In a diffuse attempt to understand these cities processes, theories began to be developed relating the functionality and dynamics of a city to the biological concept of metabolism and its transformations, which was first proposed by Schwann in 1839. This concept evolved into an incipient metaphoric description, which later evolved into the major concept of Urban Metabolism, that was first described by Karl Max, in 1883 (Newell and Cousins, 2015). The term was used to describe the interactions between the city and nature in an era of rapid expanding industrialization. The concept was later "re-discovered" by Wolman (1965), by analysing hypothetic scenarios of resource use in USA cities in 1965, all normalized to a base of 1000 inhabitant's, labelled as metabolic comparisons. His studies solidified the idea that the accountability of the cities processes and interactions of resource use could provide significant contributions to a range of different discipline areas. Nevertheless, the concept evolved into different dimensions that were shaped by specific interests presented by each field of study (Newman, 1999; Gandy, 2005; Barles, 2010).

After a few decades of sparse studies that related the cities dynamics as different types of metabolisms interpretations, it was not until Kennedy et al. (2007) that an attempt to classify urban metabolism as a framework was consolidated. He linked the concept directly to the materiality of the processes when describing it as: "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste". The author presented a quantitative comparison of a series of quantitative studies done to the date, to simply 'bring to life' the idea that through comparing different analysis done on cities resource use, a common framework could provide a base for interchanging patterns recognition, diagnostics and solutions. The framework would provide the chance of identifying similarities and trends between global cities (Kennedy and Hoorweg, 2012). Despite providing interesting insights, it can be criticized that this has somehow stimulated the comparison of data acquired at different levels and through a whole variety of methodologies being drawn together (Faccini et al., 2014; Kennedy et al, 2011).

Among an extensive variety of different conceptualizations and multi/interdisciplinary perspectives described in the literature during the following years (Castan-Broto et al, 2012; Cespedes, Restrepo & Moralez-Pinzon, 2018), three were identified by Newells and Cousins (2015) when trying to define urban metabolism boundaries.

At first, Epistemology would drive the hybridized socio-natural aspects towards qualitative conclusions of the Marxist Ecology studies (Moore, 2000; Gandy, 2004, 2005; Swyngedouw, 2006), where the theorization surpasses the necessity of accounting. In other words, description is fundamentally more important than quantification. In parallel, Industrial Ecology framed what later became the more 'traditional way' of understanding urban metabolism, moving further from the theoretical metabolism into a physical understanding of the urban spaces, by utilizing stocks and flows of materials, energy, water and its sub-products, through a whole variety of quantification methods, based on

conservations laws and mass-balance approaches to name a few (Warren-Rhodes and Koenig, 2001; Kennedy et al., 2011).

From this second solidified perspective, reinforced by critiques questioning the weak interrelation between these two pre-defined areas (Sun et al., 2016), a third perspective considering cities as networked ecosystems came to be considered more comprehensive, the Urban Ecology (Zhang, 2014). Feedbacks and interactions with the social fabric in such complex socio-ecological interactions (Golubieski, 2012) and their processes and causes (Pincetl et al, 2012) began being more deeply explored, reaching beyond the classical quantitative-numeric analysis. This perspective brought extra complexity and varied system dynamics approaches to the field, however it also represented a rescue of parts of the metaphoric concepts that actually gave origin to the term (Korpilo, 2014).

Different are the appeals about the necessity in bringing urban metabolism closer to cities planning, as an assessment tool, like Kennedy and Hoorweg (2012) that presented several common variables that could provide a 'mainstream analysis' basis, or, as a common perspective for approaches, like Barles (2010) through the use of predominant theoretical concepts. A turning point, came to be, the *UN Report for Efficient Cities*, presented in Currie and Musango (2016), where Urban Metabolism is defined as: "the collection of complex socio-technical and socio-ecological processes by which flows of materials, energy, people, and information shape the city, service the needs of its population, and impact the surrounding hinterland". This comprehensive perspective of the city dynamics has evolved from the original perspective that attributed an organism metabolism perspective to the city (Huang and Hsu, 2003), to the more complex and networked idea of understanding it as a singular ecosystem, as such a collection of organisms, finite 'nutrients' and its interactions through feedback mechanisms within its environment as a whole (Golubiewski, 2012) as represented in Figure 1.

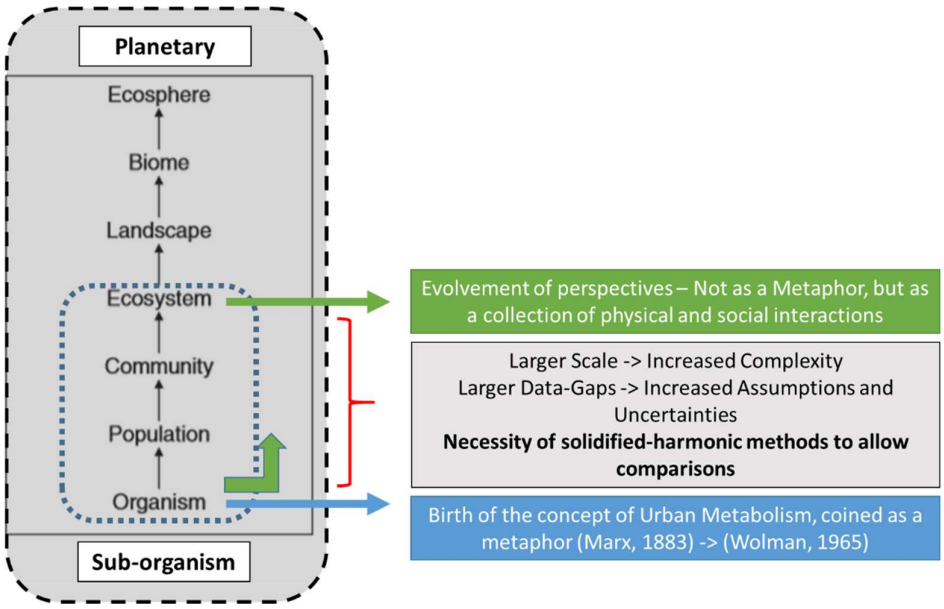

Figure 1 - Evolution of the Urban Metabolism concept, from the organism perspective to the ecosystemic view (Based on Golubiewski, 2012)

An important difference that this ecosystem perspective brings when compared to an organism, is that the greater part of outputs became potential inputs (Musango et al., 2017). This metamorphosis of the concept occurs in parallel to the shift from a linear black-box type to a circular metabolism approach described by Castan-Broto et al. (2012), and the uncovering of the black-box style approaches, advocated by Athanassiadis et al. (2015). At this point, not only cities understanding, assessment and diagnostics are linked to urban metabolism analyses, but also sustainability concepts and goals. Urban metabolism could than contribute to environmental impact assessments and efficiency analysis (Korpilo, 2014), and provide basis for other complex processes such as reuse/recycling possibilities of all the different flows analysed (Ferrao and Fernandez, 2013), exemplified in Figure 2. In this case, a composed economic wide analysis, it's useful to observe the left side column where inputs are listed, the central part of the diagram which exemplifies the internal dynamics and processes of these same resource inputs, leading to the right column where the outputs are then re-listed.

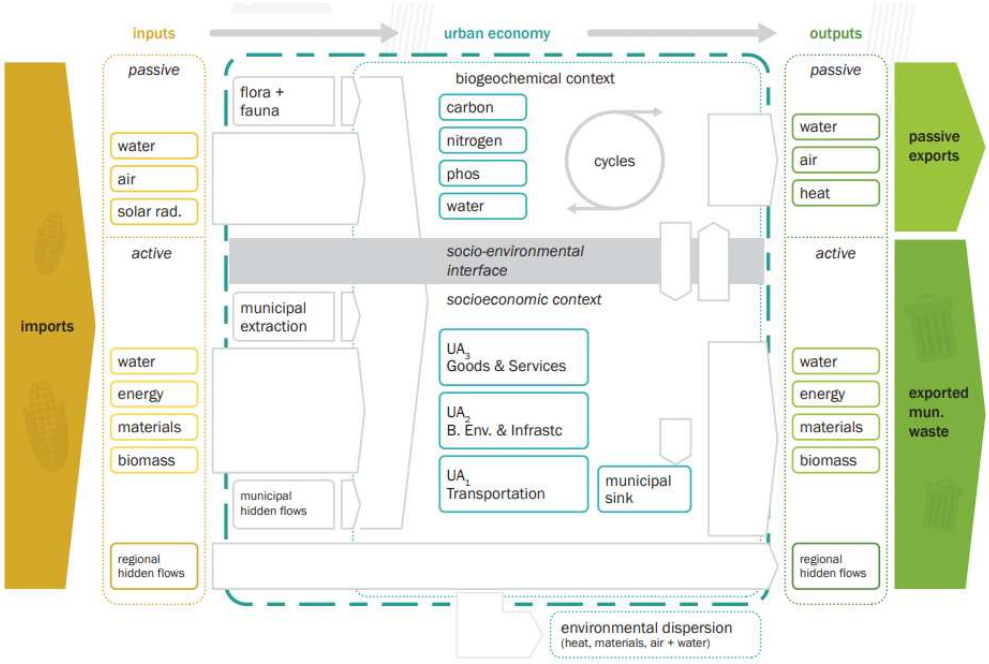

Figure 2 - An Urban Metabolism Framework Flowchart (Ferrao and Fernandez (2013) apud Musango et al. (2017)) – The blue line defines the limits of the stocks and current flows into the system, preceded by what can be considered the inputs and succeeded by the outputs, only after all the options of internal recycling/upcycling have been exhausted.

Evolved beyond theory from past decades to this date (Figure 3), urban metabolism can surely be considered a set of tools that provides scientific basis and analysis for planning and improvement of resource access, management and use in a city (Kennedy et al., 2011), as it has been promoted by the United Nations itself (UNEP, 2016; Musango et al. 2017). Energy, water, materials, nutrients and other considered elements of resources use, demands, flows and impacts are taken into consideration by several different approaches and methods for assessing and accountability of resource use, for and by, the infinite variety of activities.

These methods are used to describe, map, quantify and characterize the group of metabolic configurations of a region, usually a city (Kennedy et al., 2011; Pina and Martinez, 2014), however ranging from specific regions that are fragments of the city fabric. For example, Smit et al. (2017)

analysed a single informal settlement in South Africa in details utilizing bottom-up field work assessments, when compared to even continental scales studies, such as Wiedenhofer et al. (2015), whom analysed the whole EU25 group in a single study, using a pre-defined methodology (Eurostat, 2013) for accessing materials stocks and flows, using a bottom-up economic data from formal areas.

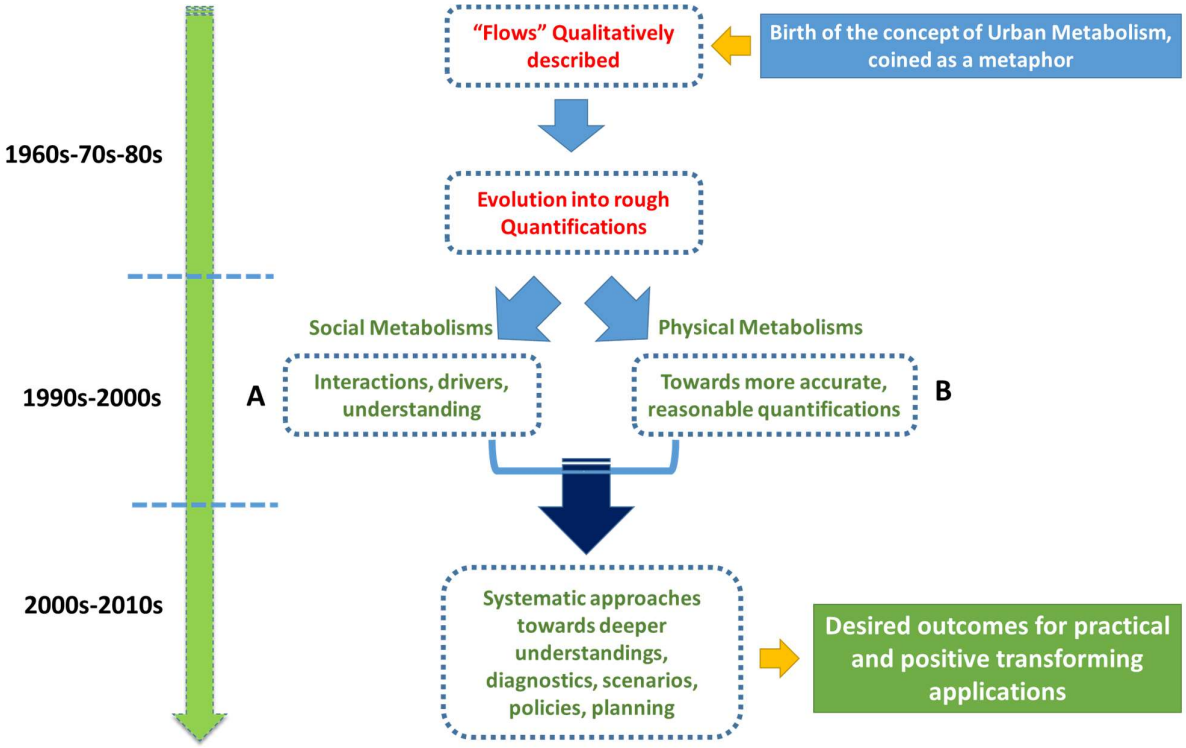

Figure 3 – Outline of the evolution of Urban Metabolism over time. The different perspectives that were drifting apart are now being faced as a single major framework to generate useful outcomes.

Nevertheless, it seems crystalized into the scholarship that there is a need to improve the transition to the actual opportunities of the application of results and discussions into cities and national resource planning and its management scope in practice, through descriptive analytical frameworks, decision-making models, and resource flow models (John et al., 2019). In the next sessions, some common urban metabolism methods will be discussed, and their past and present applications are presented and discussed as a form of guidance towards this work focus of analysing the applicability of the urban metabolism methods on global South cities, more specifically, on their Informal Urban Settlements.

2.2. UM Methods and Critiques

Building up, more significantly, from the beginning of the century, multiple methods surged to compose the variety of approaches used in urban metabolism studies (Zhang et al., 2015). Commonly, approximately five main categories can be identified. Different ways of grouping them are presented by different authors in the literature, which can vary slightly from the ones here presented. The classifications and considerations here used derive from some of the most recent reviews of the field

done by Zhang (2013), Zhang et al. (2014), Beloin-Saint-Pierre et al. (2017) and Musango and Currie (2017). They are intended to be provide the basis for an investigation towards a mixed-methods understanding and analysis of the infrastructure, mainly the built environment of informal urban settlements.

To further specify which areas of outcomes this research intended to address, here are presented the four main applications of urban metabolism outcomes identified, according to Kennedy et al. (2011):

(I) Providing indicators for scientific validation of resource use and sustainability parameters within a city / region (Chrysoulakis et al., 2013);
(II) Greenhouse gas accounting, where the accuracy relies heavily on the quality of the quantitative analyses (Kennedy, 2009);
(III) Dynamic mathematical models for policies results analysis and impacts of its applications, over past and future scenarios (Brunner and Rechberger, 2004);
(IV) As design tools to help improve the urbanization of new areas, management of existing ones and even for reconstruction of regions affected by natural disasters (Quinn and Fernandez, 2007).

To achieve these objectives, previous or accompanying studies are necessary to provide a solid database. In regards of city level data in developed countries, there is a considerable variety on availability and accessibility, however, as a general rule, data scarcity is present in most of the developing countries (Currie et al., 2015) and more specifically deficient for its informal areas weather urban or rural.

A regular point raised by researchers on the field, is the apparent lack of harmony between the methods and their main components (Beloin-Saint-Pierre et al., 2017) which will also be observed and discussed. Also, it's relevant the fact that there are not many studies that tried to expand the analysis results up to the levels where it is useful for guidance, policy-making and resource efficiency management (John et al., 2019). Existent gaps and obstacles will be further discussed, however, first, a description of the methods is addressed.

The category of methods presented here are the most applied one up to date into *Accounting methods*, which a physically quantify, mainly the stocks and flows and use as they enter or leave the internal process in the analysed region. Accounting methods are further specified into 4 types:

(I) *Economy-Wide Material Flow Analysis (EW-MFA)*
(II) *Input-Output Analysis (IOA)*
(III) *Footprint Analysis (FA) - Life Cycle Assessment (LCA)*
(IV) *Material Flow Analysis (MFA*
(V) *Simulation and Modelling (S&M)*

Economy-Wide Material Flow Analysis (EW-MFA) are methods that use top-down derived economic data as inputs and outputs of the materials into accountability of the flows. At first, it would not consider the inner process within each of them. However, following tendencies across the whole field, the updated methodology presented (Eurostat, 2013), suggest the exploration of the internal flows to provide different outputs and track different flows. These types of analysis demand a considerable amount a reliable of economic data, which can be difficult to obtain separated into the desired classes (materials stocks or resource flows). If raw data is available in groups, like metals or minerals, it becomes a major restriction and source of uncertainties to subdivide this flows into the analysed one. However, this approach has been useful in analysis at the national and city level where internal process and transformations are not of major relevance to the studies, such as for detecting different trends

of resource consumption between countries (Eurostat, 2013). A major drawback of these methods are the fact that they rely on national level data that is difficult to be scaled down to study different or specific regions of a city.

Input-Output Analysis uses a similar approach based on imports and exports but mainly through processes of empiric or practical investigations when brought into the urban metabolism field (Zhang, 2013) by adding physical data the system. Leontief (1951) first proposed it as a way to understand the economics of certain regions and it was adapted to account for any major metabolic flows within them. Input-output analysis is based on input-output tables, it has been used to account for such as water (Hite and Laurent, 1971), energy (Chen, 2011), and recycling (Liang and Zhang, 2012). The drawback of these types of analysis is that it requires strict data inputs, which may be not available. It can handle large scale sets of data, normally at national level being scaled down (Musango and Currie, 2017), as the energy wasted in internal processes and transformations are embedded into quantifications. This may be a major restriction to its application in smaller regions or data scarce areas when objects of study.

As environmental impacts and concerns worldwide became intensely discussed, especially within the climate change issue, a new set of indicators were highlighted as important, leading to the creation of a *Footprint Analysis (*Wackernagel, 1999). It does account stocks and flows for a ratio of a certain indicator per unit, which can be surface land, resource use or carbon emissions. These c*arbon-based analysis,* usually reduces the specific analysed activity and its involved resources a single indicator. These are interesting results that allow comparisons worldwide. Drawbacks are that there is not much information contained in a 'normalized' environmental impact assessment (Dakhia and Berezowska-Azzag, 2010), and also to avoid excessive regional assumptions it would need also need large sets of data to reflect specific regions realities. Nevertheless, this approach is frequently used to raise attention to the overconsumption of the planet's resources by anthropogenic activities, related to the planet resilience breakdown or the surface area needed to provide that accounting to a global ecological deficit (Musango and Currie, 2017).

Evolving from the same perspective of assessing environmental impacts of regions, *Life Cycle Assessment*, is an approach that was originally scaled up from the *Life Cycle Analysis* concept and methodologies, widely used in analysis of consumption of products (where it is given special attention to at least five different stages, ranging from extraction, production, distribution, use to their final destinations - *LCA* of each analysed flow or material). It is also called a "cradle-to-grave" approach for the same reasons (Hendrickson et al., 2010). In contrast to the former approaches, *Life cycle assesments (LCA)* are a considerably more specific and praised as tools able to provide a more "precise picture" of environmental impacts, however, there are strong downsides, such as that large sets of reliable data are necessary for it, thus rendering low the possibilities of a wider set of applications (Beloin-Saint-Pierre et al., 2017). The more complex and diverse the region of study, the harder it is to use an *LCA*. LCA is a promising tool for when details of the flows can be easily traced back, which also acts as a limitation, as even on smaller cases, it's evident that large sets of data would be necessary.

Simulation and Modelling approaches are the ones that use mathematical models for unravelling the complexity of urban relations and systems. *System dynamics* and A*gent-based modelling* are possibly the most relevant to urban metabolism future. They represent the next step into the analyses (Dooley, 2005). Modelling has a great advantage to provide numerous possibilities for different future scenarios perspective analysis, predict behaviours of the whole system or a specific flow dynamic (Musango and Currie, 2017). In agent-based modelling or cellular automata models, there is a necessity to define activities and interactions between the selected agents within a defined system. It's necessary to fully engage into the identification of drivers of the flows and process, as they are

determinant to the correct composition/calibration of any model, as well as the accuracy of these datasets. In comparison, a relevant advantage, of a systems dynamics approach, is that it opens more possibilities to the inclusion of a semi-qualitative analysis of drivers and dynamics consequences to the system, than typical accounting methods which are tightly more structured (Kuai et al., 2015).

Material Flow Analysis (MFA) / *Material Stock Analysis (MSA)* is the most widespread used between these methods. Raw-materials and resources, products, wastes and remaining stocks quantities and consumption are quantified as they flow through a defined system, as generally represented in Figure 4. These methods are overall used for numeric or mass-based quantifications of the environment stocks and throughputs, such as the buildings and infrastructure stocks, energy, water and waste flows. The resulting variables include quantities and indicators of: material consumed, stocked and throughputs per capita, sqm², or dwellings, depending on the stocks and flows analysed, easily transcribed into carbon emissions and its by-products (Brunner, 2007). This method, which composes the main scope of the qualitative part of the research investigation and proposed methodology is further discussed along the next sections.

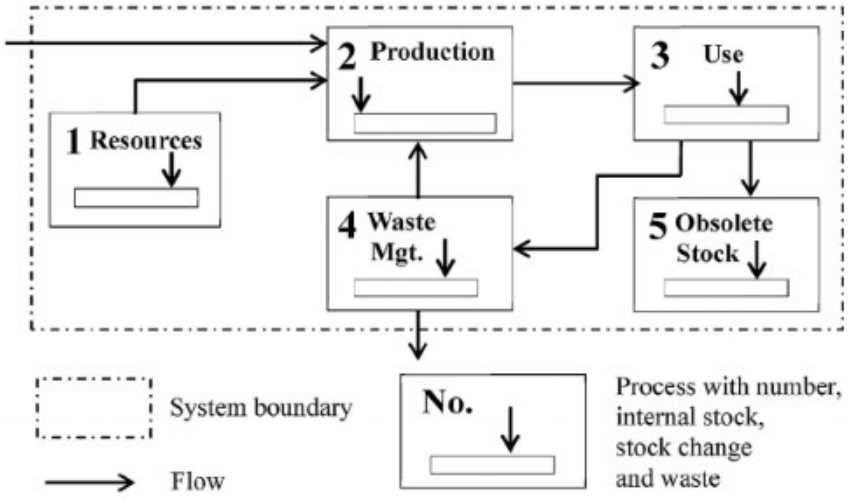

Figure 4 - A general MFA system as described by Li and Kuan (2018)

In addition to these boundaries, as such complexity is inferred in the urban metabolism studies, different methods started being combined and used together to compose Hybrid methods aiming to fill "blank" spaces and address limitations that certain methods might leave when extending their scope further than its original conceptions (Musango and Currie, 2017). For example, spatial analysis tools such as remote sensing and geoprocessing can be used for detecting similar areas where the same parameters can be applied, or for scaling up or down inputs or results in accordance, resulting in hybrid mixed-methods approaches (Korpilo, 2016). This is especially useful for non-equilibrium approaches such as bottom-up MFA`s.

Macroscale analyses of big cities, such as the study by Facchini et al. (2017), analysing the energy metabolism of megacities, provides some insights into how resources are being used, but it also potentially misleading, by taking too many assumptions and adjustments. A risky example in this study is the energy consumption numbers for some of the cities analysed being scaled up and down linearly from national-level data. Assuming a flexibility of an indicator that it's known to be not true, as the

denser the areas, they tend to consume less energy, is one of the several identifiable factors influencing it. Therefore, the data collection / availability and the scaling of the analysis, are once again fundamental aspects that provides a duality in benefits and risks.

The same concern is valid when there is an intention to compare results and outcomes among different studies when there is a considerable lack of standardization of methods, recognized by different authors (Zhang, 2013; Fernandez, 2014; Currie et al., 2015; Musango et al., 2017). Despite some extensive multi-city comparative studies being done, in four major studies that compared materials metabolism in different countries, none have used the same methodology, neither for data sourcing/collection, neither for comparison (Decker et al., 2000; Kennedy, 2007; Saldivar-Sali, 2010; Kennedy et al, 2015). What is clearly deductible is that the urban metabolism field still on a stage of progress where data availability is a major concern, but also this absence of a solid standardization is due to the same reason, as shown that studies are done with the data is available, leaving informal areas largely overlooked, which will be discussed in the next section.

As a result of the large set of methods available used to understand the city (or target region) using the urban framework, different outputs may support different outcomes in studies. Accounting methods such as *MFA* help diagnose and predict resource use with more accuracy and a better understanding, and also setting grounds for other studies, as they can serve as actual primary data generation sources. This can be or not, accompanied by policy suggestions and recommendations for specific regions or actors of the urban space, stakeholders such as industry or government for example. In informal regions of developing countries, it's imperative to perceive and design the applicability of this methods as a decisive major step.

A common point to all methods is that outcomes are intended to aid the resource-efficient cities and explore socio-economic interactions (Musango et al, 2017), that are intrinsic to all cities, across different scales as represented in Figure 5 (Zhang et al., 2014). From the diagram it can be observed that there are multiple levels of analysis, in the present research the focus is into the 'UM' level. If data scarcity was not the major limitation, as a knowledge gap regarding the infrastructure of informal regions, the same would be valid for *Energy-based analysis* and its integrations, the broadness of access and use, ranging from residential, industrial, up to national level. *LCA* and *Ecologic Footprint analysis* may be vital for quantifying, tracing, capturing and identifying patterns and issues of environmental impacts, both already caused and to decrease or raise awareness for future potential. *Simulation and Modelling* could provide specific insights that would not be empirically observable, thus, also serving as support for policies and recommendations.

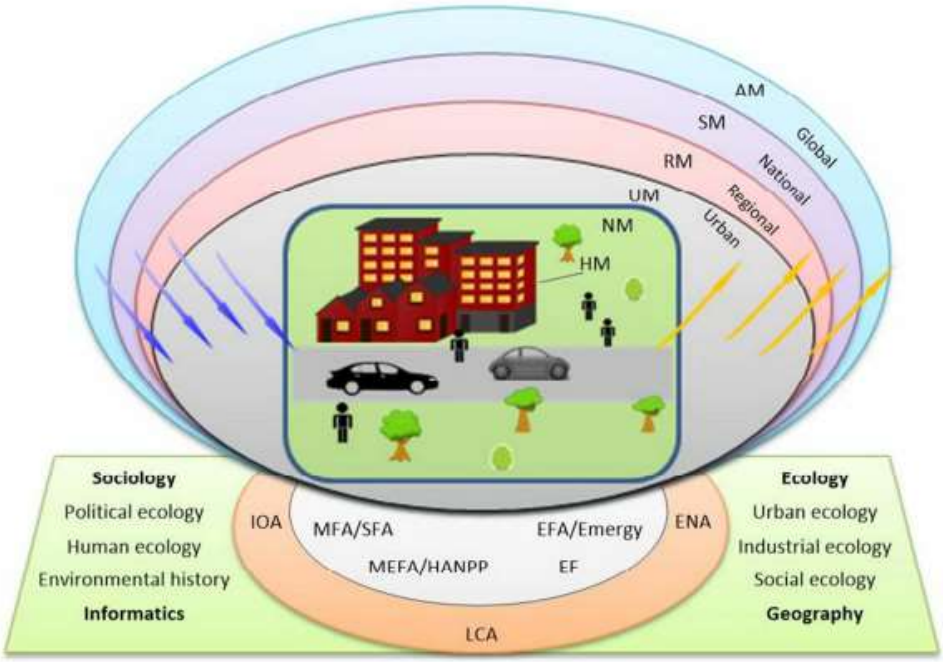

Figure 5 - Multiple scales and disciplines that can be considered in studies of urban metabolism. Notes: AM, anthroposphere metabolism; EF, ecological footprint; EFA, energy-flow analysis; ENA, ecological network analysis; HANPP, human appropriation of net primary production; HM, household metabolism; IOA, input-output analysis; LCA, life-cycle assessment; MEFA, material- and energy-flow analysis; MFA, material-flow analysis; NM, neighbourhood metabolism; RM, regional metabolism; SFA, substance-flow analysis; SM, social metabolism; UM, urban metabolism. Source: Zhang et al., 2014

2.3. The uneven distribution of UM studies worldwide

A valid observation is that, if there is an omnipresent requisite for most if not of the urban metabolism methods discussed, it is the necessity to be fed by, usually, large sets of data, that most of the times will be derived from past studies done at national or regional level. The quality of the data is not always fully assessable, so the sourcing of data itself will be the cornerstone of the reliability of these analysis results (Caputo et al., 2016).

Over the last two decades, a large number of studies was done using the framework all over the globe. Figure 6 shows the number of urban metabolism studies throughout recent years, by the approach each study used. It can be noticed that accounting studies represent the major part, while hybrid methods are also of greater occurrence in more recent years, indicating recent attempts to combine different methods. Accounting methods taken in to account at this graph are different MFAs approaches, in their vast majority.

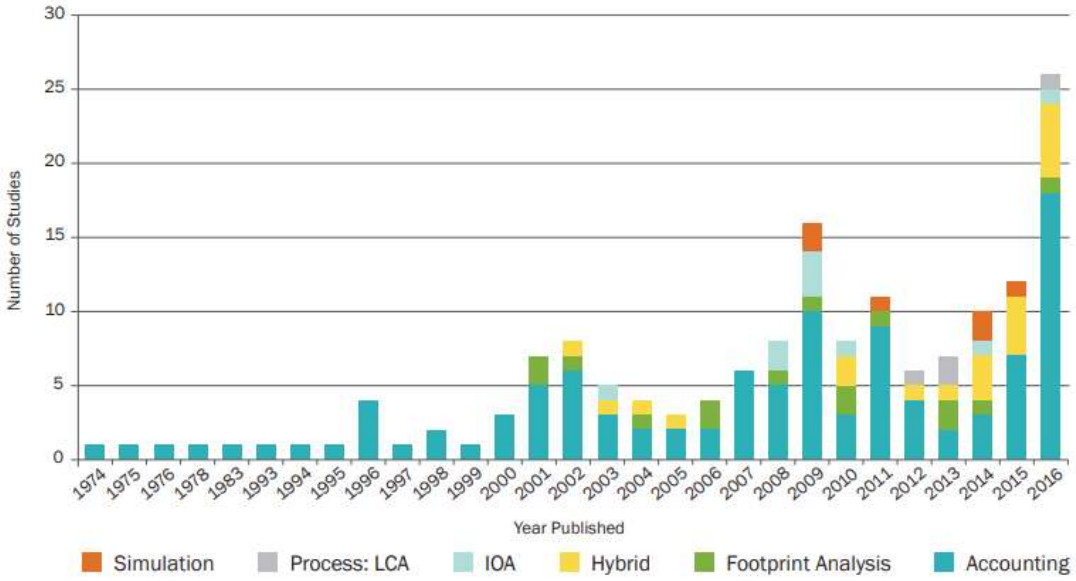

Figure 6 - Number of UM studies over time. Notice the increase in the methods diversity and consolidation of the use of hybrid methods as alternatives. (Musango et al, 2017)

However, among these 165 UM studies done at city level, that were reviewed in the work by Musango et al. (2017), 94 (56%) were done in the global North, especially in major cities of Europe and USA, and 9% were multi-cities comparative studies. It attracts the attention, the fact that only 12% (20 studies) of the total were done in global South cities (in this case, excluding China – that correspond 23% of the total of studies alone, presenting a higher level of knowledge and studies developed, much closer to global North levels).

This is observed throughout the years and can be justified by funding opportunities, data availability, accuracy and the research capacity and infrastructure offered by high-quality universities and research institutions available in the global North. Figure 7, shows the spatial distribution of these studies worldwide. It's also clear from the map that there is a significant lack of studies in Latin America (7 of 165), Africa (6), the Middle-East (1), India (1) and South-East Asia (5). The intrinsic differences alone could tend to render invalid or not easily transferable the numerous approaches and lessons derived from global North UM studies. However, in addition to that, it's alarming the fact that these are regions where data scarcity is frequently the case (Currie et al, 2015) while these studies / knowledge gaps keep growing.

Figure 7 – The orange line approximately delineates the global North x South division. There are evident data gaps and scarcity for studies on the global South, particularly in Latin America and Africa locations. In contrast, the global North and East China region shows a considerable number of studies done. (Adapted from, Musango et al, 2017)

While Megacities will keep emerging in an unbalanced / unequal developing world, it is a major concern that, still, there is a considerable lack of understanding on the dynamics and impacts of resources use and metabolic configurations of the global South as a whole (Fernandez, 2014; Currie and Musango, 2017; Schindler, 2017). The most significant urban growth over the next decades will be concentrated in the global South region (UN, 2018). Therefore, researchers are raising concerns and urging for the investigation of questions aiming to be increasingly aware of the resource use, demand, pressure and consequences that occur in global South urbanism, considerable in areas that have intense population growth, rural to urban areas migration and thus rapidly expanding urban areas (Demaria and Schindler, 2016; Schindler, 2017).

Global South cities presents today one of the biggest challenges for solving the majority of social economic and environmental unbalances worldwide (Smit et al, 2019), conditions that are reflected in all resource use levels. In addition to the pace of the urbanization, the unique and *harder-to-predict* urbanization pathways of southern urbanism, favours prejudice / marginalization in other aspects such as: land use conflicts, resource and infrastructure access restrictions, housing and employment deficits, lack of adequate policies and the questionable power relations present themselves in much more unequal and unfair distribution when compared to the global North (Musango et al, 2017).

2.4. The infrastructure beyond the networked city in the global South regions

Despite the lessons learned from the global North development and the fact that new studies keep reaching further, obstacles arise when trying to bring these lessons and theories to apply in the global South cities. For different reasons, the urbanization phenomena, patterns and process occur in

naturally different ways in the global South when compared to global North, posing a new paradigm on the Southern urbanism, yet to be fully understood, described and explored (Schindler, 2017).

The general lack of normative planning renders a strictly less formal and more heterogenic, usually chaotic urban environment. It is defined as a different form of urbanism, in a series of inner-city reconfigurations described as splintered urbanism by pioneers Graham and Marvin (2001) and a reality of the post-networked city era (Rutherford and Coutard, 2015). Splintered urbanism is a definition that challenges the formal networked city, where homogeneous infrastructural spaces, norms, conventions are expected to be met, and therefore, the city inhabitants would live and have access to similar levels of the *experience of the city* (Graham and Marvin, 2001).

These cities would have evolved through a lack or decentralized planning and investments restricted to specific areas, decentralizing the idea of living the same experience, and providing room for different adaptations and reconfigurations of the infrastructure within the city (MacFarlane and Rutherford, 2008), leading to a spatial (and social) splintered experience of part of its inhabitants, dictated by specific local characteristics and not through the rule of a central government (Rutherford and Coutard, 2015).

However, it does not apply to all of global South, as for example in Latin America, Perlman (2010) describes parts of the infrastructural spaces of Rio de Janeiro, a city where informal settlements have been established for approximately 140 years now. The informality was always present, since the end of slavery times. And in fact, these spaces have never been truly connected to the city network spatial development, despite sometimes being literally in-between future networked areas. Therefore, they could not be *splintered*, as they were occupied, auto-constructed, ruled and managed by its own local residents, marginalized, since the first moment.

On the other hand, a similarity between most of global South cities, is that the infrastructure configuration has been a key element of contestation (Guy and Marvin, 2001), where informal settlements represent the maximum level of expression of community appropriation and political transformation of infrastructure. Almost as done *by force*, in attempts to resist the marginalization, meet social needs, and the provision of the necessary natural resources through technological adaptations and improvisations, classified as a “life support system” (Coutard and Rutherford, 2016).

Despite these unbundled deregulated spaces having their own self-organizing capacities, security or land tenure is more than often not present. So policies for dealing informal urban settlements evolved into different layers of strategies, not only limited to the physical urban aspects (Young and Lieberknecht, 2018). Local development, relocation, eviction, removals, regularization and rights, legal possession processes are among them. These processes which changed through the decades and can be categorized as incremental or experimental. Incremental policies are based on past experiences and are more applicable to deal with situations already faced in the past. Experimental policies are the ones that have not been applied in the past, and, therefore are accompanied by higher uncertainties on outcomes (Silver, 2014) and quite often negative implications are neglected in their implementations (Roy, 2015).

Even though informal settlements are more likely to be vulnerable to policies and decisions that can cause sudden changes (such as eviction, forced reconfigurations), these spaces have a considerable capacity to organize themselves in particular forms of local government, community empowerment, and address local resources use and management, frequently offering interesting observations (McFarlane, 2103), and potential lessons of how infra-structure access for housing and services works

outside the formal planned city (Musango et al, 2017). This whole body of scholarship can subsidise a more reasonable path towards the inevitable hybridization of the formal and informal spaces being contested as parts of the same experience, the same social space.

To achieve that, and oppose inequality with policies, informal settlements must be recognized as legit and *ever-present* configurations of the global South, and not only seen as abnormal discredited forms of occupying the urban space (Fernandez, 2014). Increasing characterization and critically assessment of informal urban settlements across different scales is necessary (Dijst et al, 2018).

Finally, it is important to mention that, the modern 'formal network' is usually barely implemented in these spaces. This provides an opportunity to use urban metabolism concepts as a window into understanding the actual configurations to support the development of more efficient and adaptive infrastructure forms. However, as these spaces are very dynamic and suffer rapid growth and changes, if strong grounds in the field are not set, the future developed methods will keep in the shadows of the risk of being quickly outdated (Kovacic et al., 2016). It's rather relevant that this is a more rational approach than trying to force a movement through the same former processes of infrastructural development presented in global North cities, many of which, despite its status and importance, are now judged as inefficient urbanistically and ecologically unsustainable (Kennedy et al, 2011; Fernandez, 2014; Rutherford and Coutard, 2015).

2.5. Informal Urban Settlements

Africa, South-East Asia and Latin America are the parts of the world where are concentrated the existence of informal urban settlements. Widely common to most their countries and cities, they are a regular presence in the urban space, not an exception (Smit et al., 2017). The existence of significant resource use inequality and infrastructural disparities and are often related to the presence of informal urban settlements and its vicinities in global South cities.

As cited unplanned rapid urbanization pathways generate marginalized urban spaces that constantly try to *stabilise* themselves in the city as part of the formally recognized and privileged spaces. Despite the fact, informal regions of the city often play a considerable role into cities economies and labour force, which raises the necessity of cities politicians, managers, planners to at least allow them to maintain its own economic viability (Dovey and King, 2011; Roy et al., 2015). Therefore, when this type of inclusion or "recognition" as part of the city is acknowledged, it happens despite the fact that the lack of investments results in its inhabitants more than often having basic rights as citizens neglected, which ties a contradictory situation, as they are kept socially marginalized even when formally recognized (Pearlman, 2010).

Further exploring, it creates contradictions on the legality and rights of dwellers to occupy these spaces, and governments interests tend to dictate case by case (Bjorkman, 2014). Government sporadic interventions, aimed at keeping the control and city income on taxation and basic services *charging* are examples of forced inclusion of these spaces as formally recognized areas (Bjorkman, 2014). Up to date, despite 50 years of different policies put into place, through interventions, demolitions, displacement and local upgrading, they all seem to have failed to halt or suppress the overall growth of these areas (Dovey and King, 2011). It is estimated that 1.4 billion world inhabitants were living in Informal Urban Settlements by 2020 (UNEP, 2016). The vast majority in the global South, along increasing urbanization trends. The actual rate of informal settlements population reductions

(Table 1) was overcome by its growth during 24 years, neither in Latin America with a higher proportion of urban population or Sub-Sahara Africa with a much lower proportion.

Table 1 - Urban population percentages and percentage of the urban population living in informal settlements by continent over the last decades. (UN-Habitat, Slum Almanac Report, 2016)

Proportion of urban population (per cent)								
Major region or area	**1990**	**1995**	**2000**	**2005**	**2007**	**2010**	**2012**	**2014**
Developing Regions	34.8	37.4	39.9	43.0	44.2	46.1	47.3	48.4
Northern Africa	45.7	47.3	48.4	49.4	49.9	50.5	50.9	51.4
Sub-Saharan Africa	27.1	29.1	30.8	33.0	33.9	35.4	36.4	37.4
Latin America and the Caribbean	70.5	73.0	75.3	76.9	77.6	78.4	79.0	79.5
Eastern Asia	33.9	37.7	42.0	48.3	50.7	54.3	56.7	58.9
Southern Asia	26.5	27.8	29.1	30.8	31.6	32.7	33.6	34.4
South-eastern Asia	31.6	34.5	38.1	41.3	42.6	44.5	45.8	47.0
Western Asia	61.1	62.4	63.8	65.9	66.8	68.1	68.9	69.6
Oceania c	24.4	24.2	23.7	23.4	23.2	23.1	23.0	23.0

- Increase
- Urbanization Trends

	Proportion of urban population living in slum (per cent)							
Major region or area	**1990**	**1995**	**2000**	**2005**	**2007**	**2010**	**2012**	**2014**
Developing Regions	46.2	42.9	39.4	35.6	34.3	32.6	32.7	29.7
Northern Africa	34.4	28.3	20.3	13.4	13.4	13.3	13.3	11.9
Sub-Saharan Africa	70.0	67.6	65.0	63.0	62.4	61.7	61.7	55.9
Latin America and the Caribbean	33.7	31.5	29.2	25.5	24.7	23.5	23.5	21.1
Eastern Asia	43.7	40.6	37.4	33.0	31.1	28.2	28.2	26.2
Southern Asia	57.2	51.6	45.8	40.0	38.0	35.0	35.0	31.3
South-eastern Asia	49.5	44.8	39.6	34.2	31.9	31.0	31.0	28.4
Western Asia	22.5	21.6	20.6	25.8	25.2	24.6	24.6	24.9
Oceania c	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1

Progress in 24 years
14.1% (AF)
12.6% (LA)

As defined by the UN in 2012, Informal Urban Settlements is "a conglomeration of slum households", a certain is presented to represent the as whole physical and spatial manifestations of urban poverty and inequality (same definition used on approaches by Smit et al, 2017; Kovacic and Giampietro, 2017). The criteria defined is to have one or more conditions among the following:

(I) Inadequate access to safe drinking water;
(II) Inadequate access to sanitation and other basic sanitation infrastructures;
(III) Deficient housing structural conditions;
(IV) Insecurity of tenure and eviction-risks,
(V) Insufficient residential area for each inhabitant (overcrowding).

Throughout the academic literature there are a few different nomenclatures (Table 2), definitions and classifications criteria for Informal Urban Settlements, that also tend to have slightly specific variations between local governments and institutions (Kovacic and Giampietro, 2017) and names such as slums, shantytowns, squatter, unplanned, deprived areas or settlements (Kuffer et al., 2016). Poor living and housing standards are ever cited in general classifications. Restrictions on access to basic services and infrastructure are specified as a major part of what characterizes the informality of the physical materiality within the city.

Table 2 – Frequency of terms found on publications (limited to the remote sensing area). Source: Kuffer et al, 2016

Terms	Frequency	Percent (%)
Informal settlement/area	41	47.1
Slum	25	28.7
Slum and informal settlement/area	5	5.8
Squatter area	4	4.6
Unplanned area	3	3.5
Deprived area	2	2.3
Refugee camp	2	2.3
Sub-standard area	2	2.3
Informal homesteading	1	1.1
Informal and unplanned settlement	1	1.1
Migrant and informal housing	1	1.1
Total	87	100

Other Informal Settlements studies present classifications that are related to the physical characteristics of the built environment (Dovey and King, 2011). However, these approaches tend to ignore, or, are simply unable to capture the heterogeneity of the social inequality, informality, power struggles and political interests that go along with the informal urban settlement's establishment and development (Kovacic and Giampietro, 2017). To move forward in the path of accessing the informal infrastructure within these spaces, it should also be considered the economics, social dynamics and local politics (Hare and Barke, 2018).

Informal Urban Settlements tends to establish in areas where the formal housing market is non-existent, or on opportunities such as waterfronts, escarpments, easements, enclosures and other public spaces, represented in Figure 8. Three primary processes of Informal Urban Settlements growth can be considered (Dovey and King, 2011):

(I) Setting in unclaimed or unbounded lands;
(II) Inserting into uninhabited and leftovers spaces and buildings in the city;
(III) Attaching to already constructed structures of the formal city.

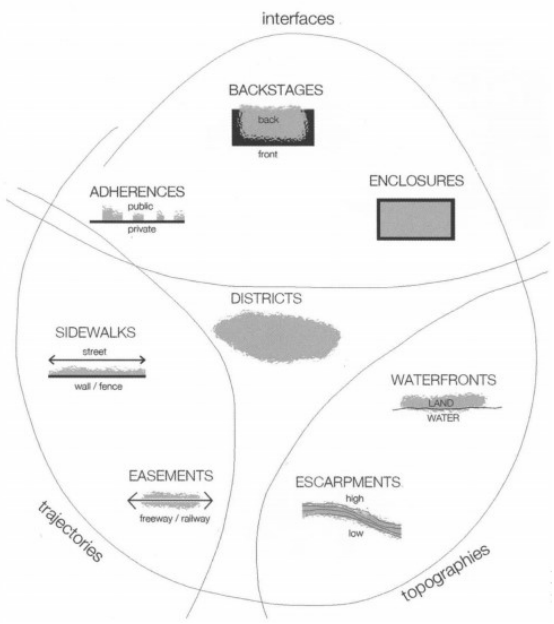

Figure 8 - Some Informal Urban Settlements typologies (Dovey and King, 2011)

For a long time, Informal Urban Settlements have been studied as a separate cluster inside the city and considered only its physical, geographical and legal characteristics. Smit et al. (2017) argue that the relations and connections that they have with the formal parts of the city are the major factors that should be understood to clarify the metabolism of these areas. Roy et al. (2015) classify the relation of an Informal Urban Settlement to its containing city as commensalistic, where slums in a city serve certain functions and provide the workforce to formal areas, or parasitic when slums are a detached organism that creates a strong dependence on the city resources for prospering.

However, Demaria and Schindler (2016) previously contested these ways of understanding with reflections on their studies on Delhi waste disposal cycles, pointing that there is a co-constitution of the materiality and the political economy of the cities, including among them their informal spaces and the many services provided by them, as, for the fewer services in place for them.

Therefore, the infrastructural (re)configurations in the informal fabric of a city, can be strongly driven both by: (I) its internal community motivations and aspirations, and executed by themselves, which are derived also from being part of the city experience as a whole while being marginalized at the same time, or (II) could be directly connected to city-scale political governmental decisions that are developed, planned outside these spaces, without its local demands being directly obtained or attended.

These facts reinforce the importance of an approach towards the concept of hybridity, in which the view of formal and informal areas segregation is pushed aside to give space to observations where the interconnections within the urban space transformations can be understood as being part of the same urban environment (Schindler, 2017). This is what permits the mixing of quantitative data analyses of the materiality of a city (housing, buildings and infrastructure), its changes over the years (temporal analyses), supported by qualitative analyses of both physical, social and political aspects, observing and assessing, and embedding at least some, major drivers and consequences.

Contradicting these lines, these areas are often neglected in city-level studies, mainly by technical reasons related to data scarcity (Condeixa et al, 2013), but also to possibilities of data collection, due

to precarious infrastructure and risks such as high crime rates, violence, poor health environments among other common issues (Roy et al, 2015). Thus, understanding the physical characteristics, growth, and the social-economic role played by informal settlements could have serious direct impacts on local urban planning, management and possibilities of policymaking. For instance, In Brazil, where the majority of the population lives in already saturated cities, in 2010 there was a total of 11,5 million persons in this situation, corresponding to close to 7% of the population (IBGE, 2013). In India alone, 17,4% of urban households are located in slums, comprehending more than 200 million people (Census of India, 2011 – Apud Roy et al, 2015), in a fast-paced ongoing rural exodus.

It is evident that, in several developing countries (specially located in Africa and Asia), if patterns don't change, a fact that is not expected, there still to happen an enormous population migration from rural to urban areas worldwide, leading to enormous pressure over environmental resources at local and global scales. Therefore, if policies are not able to give the necessary support, ever larger urban populations will be condemned to live in Informal Urban Settlements (UNEP, 2016).

In addition to that, triggered by different economic reasons, already saturated urban spaces such as some Latin American cities are experiencing a downgrading (as such class mobility movements), displacing populations that were already settled in lower classes formal areas into older ever kept-marginalized areas or even contemporary newly formed informal settlements. Evidence of this was described by Cavalieri and Vial (2012), who found out that in a period of ten years (2000 – 2010) in Rio de Janeiro, Brazil the total urban population grew 8% in total. However, in the areas considered as Informal Urban Settlements, the population grew 19% compared to only 5% if the same numbers were kept limited to the formally recognized areas, excluded all 'favelas'.

Therefore, even taking a new perspective towards informal settlements as an integral part of the city, in practice, internal community-based transformations/adaptations and local problem-solving practices, creates a contradictory ambiguity of having at the same time characteristics and on-going activities that are often described as part of formal and informal settlement (Roy, 2005; Bjorkman, 2013). This thin line of continuous transition between legitimacy/illegitimacy has also been explored by Smit and colleagues (2017) when conceptualizing slums in South Africa, as represented in Figure 9:(6-E) Hybrid, multi-structured settlements.

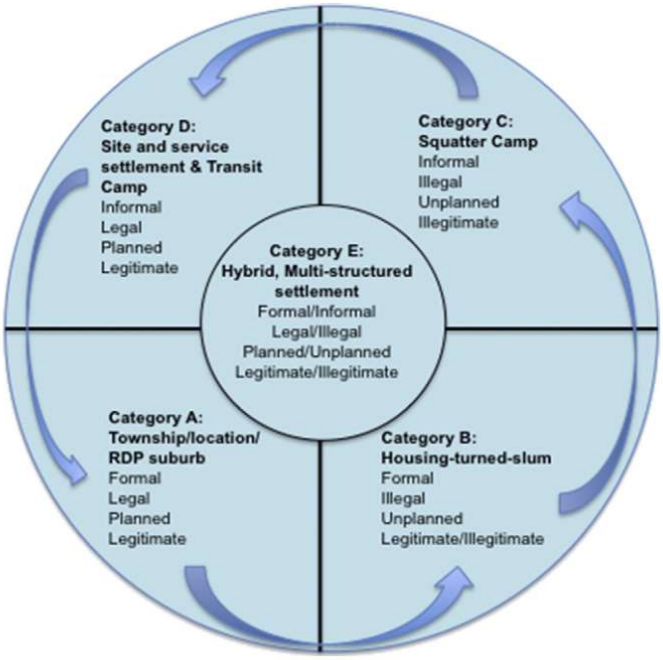

Figure 9 – Distinctive Informal Settlements typologies developed by Smit et al. (2017). Category E represents the inevitable transition between formal and informal to inclusive participation within the city social and infrastructural resource access and experiences.

The lack of planning or the result of equivocated policies, aggravates the poor living conditions on its continuity, creating a scenario where proposed solutions tend to face bigger difficulties as time passes. Key impacts and concerns on social and human aspects where summarized by Roy et al (2014), they involve:

(I) Lack of education and exclusion from the financial system;
(II) Poor health and child mortality;
(III) Entry-points to the poor, as the provision of informal income and ownership opportunities;
(IV) Political and social exclusion;
(V) Safety concerns and gender equality issues for women;
(VI) Vulnerability to climate change and natural disasters.

Key factors will have a direct influence on the emergence and growth of informal settlements (Roy et al. (2014); Smit et al. (2017)). These factors influence the ones involved (residents and stakeholders) in fairly different ways when comparing to realities found in the global North. They are:

(I) Changes in the population;
(II) Economic growth/opportunities;
(III) Housing deficit and the housing market dynamics,
(IV) The informal economy,
(V) Local topography and street occupational patterns;
(VI) Internal politics of the settlement.

Societal and political approaches will give ranks to defined social analysis questions and observations. They can be qualitative or quantitative. For example, a classification can be based on access to services and / or infrastructure deficiencies (quantitative), where the degree of deprivation (qualitative) will vary on intensity according to the possibilities which the city (in which the informal settlement is part

off) offers and how much it has obtained, therefore establishing a mixture of qualitative and quantitative analysis (Roy et al., 2014).

In terms of study approaches to better understand informal urban settlements five can be highlighted:

(I) Conceives the autonomy of the process to the community, advocating that inhabitants would gradually overcome the adverse housing conditions if provided the basics services, sanitation, urbanization and transport.

(II) A second approach tries to understand the role and transformations generated, of policies and programs, using retrospective studies for evaluations and perspectives over time.

(III) An independent view is presented by a third approach which is based merely on quali-quantitative data to analyse urban poverty and informal settlements dynamics (Patel et al., 2012). Studies can focus on specific areas to provide details or can use indicators the achieve a broader view, scaled or not, perspective.

(IV) The fourth approach is the one that utilizes digital images such as aerophotography, satellite images for remote sensing (RS) analysis over different moments of time, or it includes "dialogues" with another type of data through the use of geographic information systems (GIS) (Hoffman et al., 2005).

(V) The fifth approach considered are the ones that involve direct action, research *in-situ*, normally with the direct involvement of the community, learning, participation and mobilization, ranging from analysing conditions of particular cases to whole regions (Roy et al., 2014) by utilizing qualitative methods such as participant observations, focus groups and semi-structured interviews.

In order to further discuss the possibilities and applications of the urban metabolism methods on Informal Urban Settlements of global South cities, their overall characteristics, internal dynamics and interactions with the networked formal areas must be considered. This is also necessary to summarize the research gaps identified.

2.6. Material Flow Analysis (MFA) and its possible applications to IUSs

As discussed earlier in this review, Urban Metabolism is a tool considered for planning and improving resource use and access in a city (Kennedy, 2011). Considering the built environment, in the assessment and accounting of building stocks and constructions materials, the most common approach, that is presented in the literature is the Material Flow Analysis (Barles, 2010). Inside the MFA field, a range of different methods can be identified. The main object of the studies are the specific materials itself, their flows and transformation processes, from source to final destinations. These materials are stocked in constructions or used in constructions phases or regular flows through them, therefore its waste generation and recycling can be taken into account. The stocks and flows that constitute the built environment represents one of, if not the most important part of urban metabolism accounting of a defined region, the materials used withholds high environmental impacts in their production being responsible for a major part of carbons emissions and also tend to represent the larger share of mass and volume in the system as a whole. Material Flow Analysis (MFA) methods are here used for directly or indirectly accounting the flows of mass and matter that throughput the defined city or region (Ferrao and Fernandez, 2013).

Fischer-Kowalski and colleagues (2011) explains that analysing physical stocks and flows together are essential. They are responsible for a significant difference gap between resources demand (inputs) and wastes (outputs) within a city.

Then approaches evolved to include other important issues, apart from energy, such as materials flows, their environmental impacts and waste production, total mass flows. The pressure for resource extraction demands and predictions for buildings, infrastructure or specific materials in actual use, mapping empty buildings or urban regions, infrastructure quantification and distribution and urban land use patterns were also elements of interest (Kohler and Hassler, 2002).

When considered a bottom-up approach, methods utilize inventories of end-use objects (buildings and public infrastructure) at a specific point or short period of time. That's the reason for being also called "statical analysis". This section of the review will dedicate more attention to the bottom-up methods, as they are the most appropriate way available to understand informal urban settlements. This is based on data scarcity, and the necessity of some primary data generation/collection for the desired understandings as it will be explained through in the method section. The process for accounting exclusively the built environment constructions materials is referenced also by different names that swirl around the same idea: Buildings Stock Analysis (BSA), Material Stocks Analysis (MSA), or Materials Stocks and Flows Analysis (MSFA).

Tanikawa et al. (2015) provide a state-of-the-art review on Materials Stocks research, presenting the different line of methodologies split into four: Bottom-up and top-down accounting, remote sensing and demand driven models. Materials content are obtained from the material intensity for each analysed object or for categories, usually generalizations such as buildings and neighbourhood typologies. Mass balances can them be obtained when the different activities/objects are reduced to a single variable. This conversion enables us to estimate the amount of certain material in-use at that present time through, which are termed as "snapshots" by the authors.

Only by obtaining different timed "snapshots", or secure information, that the flows or age of these materials can be defined. The bottom-up approaches are methods that are based on inventories of the physical and spatial data analysis. Quantitative data such as building quantities, lengths, volumes, and mass are related to their materials composition and insensitivities, being normally categorized in buildings typologies/infrastructure types to provide a total quantification of the desired materials. Bottom-up case studies tend to include more details and characteristics of the specific materials intensities and flows (Tanikawa et al., 2015), which are less difficult to be obtained or observed when data is generated at the base level. Unknown variables and uncertainties become easier to be dealt with, a fact that alone makes these types of approaches more applicable to the IUS reality.

Conclusions of one of the major bottom-up studies done involving 25 EU countries point to the importance of considering the size of stocks and their lifetime as the most important drivers of material use (Wiedenhofer et al., 2015). A reduction is most likely to be obtained by the "stabilization of the existing stocks" and prolonged service lifetimes of both public infrastructure and buildings. Critically, maintenance and net expansion of roads should be taken into consideration as major drivers of consumption (For example, evictions and displacement followed by demolition and reconstruction of informal urban settlements).

Remote Sensing and GIS MFA approaches are the methods that use aerial/satellite images They are complementary or must be complemented by another type of analysis (Pina and Martinez, 2014; Mesta et al., 2018). However, they can be considered also be partially considered bottom-up approach as they do not rely directly on the availability of local data (2D / 3D / 4D), but they will need some sort of similar data, to be used as a reference, for interpretations to identify regions with similarities to already known ones. This type of data may be obtained from other areas when considered appropriate.

Also, it is worth mentioning that a combination of two or more of the methods can be used together (Musango et al., 2017). For example, a bottom-up or top-down approach can be used to have greater details of a past or present time, and the data outcome can them be modelled to try to predict future scenarios and policies applications. A spatial analysis could be well enhanced with this sort of collaboration between different types of methods, each one with its advantages and disadvantages. For all of the above-mentioned methods, the availability and accuracy of the input data is a major concern.

2.7. Conclusions

Several authors conclude that Urban Metabolism is on its path towards being fully accepted as a tool and inferred by agreements on the scholarship development. Barles (2010) highlights, that to the date the theoretical field of urban metabolism was still unconsolidated, and it's necessary to even define the epistemology, and a stronger link between the approaches and objects of study, and also accounting of materials and flows, so that studies and actions taken in the field can be more accessible and reach further than quantitative characterizations and theoretical descriptions.

Definitions on the scope, to outline common grounds have been made by Kennedy and Hoorneg (2012) and pushed to further extent by Beloin-Saint-Pierre et al. (2017). The study highlights that only an average of 65% of the analysed studies comprehends any sort of environmental sustainability analysis and around 45% of them was meant to provide resources for decision makers. Athanassiadis et al. (2015) analyses energy drivers in several major cities at micro-scale, and points to the conclusion that at micro-scale more complex variables arise therefore there is a need to further research into how energy is been used and distributed at the micro-scale level in developing countries

Authors point to the necessity to leave behind the black-box approaches which tend to be incomplete and hence the importance of more depth when analysing the metabolism of cities within the framework. Combine the I/O-A and other UM frameworks together (Athanassiadis et al., 2015) for temporary evolution combined with spatialization, indirect effects and the identification of drivers are a few of the cited options. The use of demand-driven models can help in the understanding of the individual level actions and consequences, which are often neglected or not accounted in meso/macro-scale analysis (Zhang et al., 2014).

Castan-Broto et al. (2012) also tried to delineate the dialogue of urban metabolism with other fields and disciplines and identifies six different urban metabolism themes. These fields can be all be considered in an informal settlement metabolism as well as the example of the city. The value of the concept in practice has been questioned as a way of attracting attention to the necessity to set grounds on how to execute the transitions from theoretical studies and analysis to practical implementation aiming to promote changes to achieve better resource-use efficiency. (Kennedy et al, 2011; Musango et al., 2017)

However, outcomes achieved through some of these studies with direct and indirect implications, are already noted, such as: recommendations on new policies on waste, materials, for substitution, inclusion or demand management strategies, where to focus to strength links within the city or not, set standards, when not just providing useful resources for a better understanding of the activities impacts (Barles, 2010).

To conclude, on recent reports authors the necessity of moving from a top-down majority (Beloine Saint-Pierre et al., 2016, found 65% of the MFA studies used top-down data) to bottom-up approaches, to be able to capture and achieve higher comprehension of processes that lack conventional data, with new transdisciplinary approaches and spatial-temporal linked analysis. The use of modelling and simulations are often the way to examine complex micro-scale level interactions but also rely on variables that can be difficult to be obtained (Musango et al., 2017; Smit et al., 2018).

Just "rethinking" the Urban Metabolism towards informal settlements perspective is an important step towards understanding cities of the global South (Fernandez, 2014), and more specifically informal settlements, as not a separate part of the city (the duality of formal x informal, legal x illegal, ideal x non-ideal, networked x non-networked – Bjorkman, 2013), but as an integral part of global South cities metabolisms. Despite data concerns, all the efforts necessary should be taken to make possible the theoretical framing / practical understanding of these areas as such, in order to address the true value of urban metabolism to support resource-efficiency interventions and sustainable developments goals (Musango et al., 2017).

From the past sections, can be added that Barles (2010) provides two perspectives on the reasons for urban metabolism studies, that are reinforced by Musango et al. (2017). They are research and decision support, which examines processes to understand necessities and needs for the necessary and/or observed interactions. The other considers the necessities for higher efficiency when dealing with sustainable development challenges, which brings into a play a necessity of concept change, changing the perspective from basic optimizing the processes to changing the basis of them. In both of them the understanding of the drivers is necessary, therefore, the role of personal level interactions and the community (or city level) power relations is a common interest with the political ecology field. This presents a considerable gap to be filled, bringing closer to harmony the qualitative theoretical approaches of urban studies to the more quantitative urban metabolism field, pushing further the possibilities of representing the political realities of a city/region (Newell and Cousins, 2012).

Considered that traditional methods are not able to address new lines of inquiries that arise from the transdisciplinary studies and discussions present today (Fernandez, 2014; Musango et al, 2017). Hybrid methods studies present a way of avoiding the traditional obstacles for each of the approaches, using the application possibilities of each of them to fill the gaps they can present themselves, as some of the approaches related to informal settlements and data scarce environments, presented in the literature (Giampietro et al. (2006), Currie et al. (2015), Smit et al. (2018)).

A hybrid approach provides the possibility of focusing on more than one indicator comprehending different issues (on sustainability, living standards or resources access for example), and also target different outcomes. Musango et al. (2017) state that the is an increase in modelling and simulation methods aiming to investigate the complexity of dynamics within a city. When considering Informal Urban Settlements worldwide it's noticeable that there is a considerable lack of data to support this research progress.

Despite the discussion on the need for standardisation of the methods (Kennedy et al., 2011, Zhang et al, 2014), when considering Informal Urban Settlements there is not a significant body of literature at present, therefore, it can be drawn that it is important to define a hybrid method to set grounds on the possibilities of comparison with different analysis, but not a standard method. This is justified by the fact that at this stage of research its necessary to be alert and able to capture the particularities of the specific case to provide a deeper understanding of the processes and provide insights into the hybridization of the formal/informal interface within the city, aiming for more accuracy on quantifications, rather than just a comparable generalization. That would be a reality that is justifiable

in top-down studies on formal occupations, but not when generating primary data on bottom-up approaches. Data scarce environments might benefit from bottom-up approaches (Musango et al, 2017), especially because there is a necessity on the understanding of the informality within them that is mostly captured on ground level.

Based on the same justification, another gap identified is that it could be useful, to include methods that are able to capture individual level "behaviour-related" data (Musango et al., 2017, Smit et al., 2018), in addition to the quantitative flows and its set of drivers. This gap is particularly interesting when analysing informal settlements, as interactions occur in different ways through micro-scale level personal or collective actions and behaviour shifts. Looking further into research possibilities, analysing informal settlements as an integral part of the city (Schindler, 2016) will require a transition between the different scaling levels. This holistic view is an obstacle identified at Musango et al. (2017) and addressed by recent projects. (Kovacic et al., 2016, Kovacic and Giampietro, 2017, Smit et al., 2017)

Summary of most significant overall research gaps:

1. Lack of studies, especially bottom-up approach ones.
2. Need for more data generation in informal regions at ground level, as city level does not represent the reality of these spaces. Methodologies for understanding the flows, stocks and social drivers at base-level in global South cities.
3. Standardise methods worldwide + Increase the relevance to policy and decision makers, move beyond quantifications. Importance of joining spatial, temporal and sectoral perspectives using an interdisciplinary perspective.

2.8. Narrowing gaps to be analyzed

MFA methods and steps can require large amounts of specific data, so each study tends to consider its own sources making the comparison between results inconclusive and somehow undesirable. Despite considerable progress on the field through a significant diversity of studies, the question if there really is an applicable common approach is still viewed as an open question (Musango et al., 2017). Another problem that arises when studying trying to decipher the metabolism of informal the informal settlements is the data availability itself. Despite authors recognizing this fact, little reflections are made on what are the 'solutions' to the lack of data, knowledge and uncertainties

Studies mostly considerer the city as a whole, and when specific areas within are accounted, informality can be left aside because of the data scarcity, access, governmental or legal problems (Condeixa et al., 2017). These areas are not favoured by government and they cannot be easily accessed by lack of urbanization and access to basic services. When infrastructure is present, there may be also not enough security for a proper survey be conducted (Dovey and King, 2011).

Considering the MFA studies analysed, Condeixa et al. (2017) study, despite the state-of-the-art of construction materials constituting a field of studies in Brazil, the mapping of metabolic flows and the quantification of building stocks and infrastructure has not been presented for informal urban settlements. This is only study presented in the Industrial Ecology literature that analysed the city of Rio de Janeiro and the informal areas were disregarded completely, with the problems overly cited. Therefore, however, it is not inaccurate to say that there is a lack of harmony between presented methodologies that makes difficult any comparison between the studies of MFA, as it has been discussed for UM studies in general.

The MFA approaches discussed can be useful into the achieving a quantification of construction materials stocks and flows in informal settlements. To capture the particularities of the informal urban settlements, a bottom-up research to generate primary data seems like a possibility. The literature reviewed on construction materials flows observations can be the base of its conceptualization. The path to a successful analysis is to direct the methods towards the ability to capture the diversity of dwellings, households and infrastructure into an appropriate and faithful representative variety of typologies, such as the ones that derive from large reliable datasets (Weidenhofer et al, 2016; Tanikawa et al., 2015).

A quantification of the remaining infrastructure, such as access roads and pathways and water and energy, results could possibly lead to an interesting comparative analysis with formal areas of the city. Material flows related to be considered are the access to other resources dependent on that infrastructure, such as water, energy, solid wastes and wastewater. Apart from the buildings typologies and quantities, the number of inhabitants and household configurations may have a more significant role in the flows. In this case, per capita indicators, which are widely used, may not be the best. For example, a family of five in a single house will tend to consume less energy than two couples in two houses, or five single individuals living by themselves. Therefore, if the stages of the community's development are properly understood and measured, their resource demand estimates can be more accurate than scenarios that will only consider the absolute population growth or average income (Kovacic and Giampietro, 2013).

With planned sampling, it's possible to identify and characterize the predominant materials or construction typologies and also capture different stages of it and rates of the settlement growth (houses under construction). The quality of the bottom-up generated data is crucial for the success of a detailed temporal analysis. Any statical analysis can be easily outdated, especially considering dynamic spaces such as the informal urban settlements. A temporal analysis is a way to support the capture of the infrastructure dynamics over time. The expansion and densification over time can be also be complementary assessed with the GIS/RS techniques applied to any set of recorded historical data such as digital satellite images or formal surveys available (like major Census).

2.9. Conclusions to support the methodology discussions

In summary, based on what the literature review offered – A bottom-up approach method would desirably include these considerations, as observed from the scholarship critique:

- **Visual and interactive on-site participant observations surveys –>** Aiming to provide information on what sort of construction materials are being used and the basic indicators for their quantification.
- **Constructed dwellings –>** Their approximate structure compositions, number of floors, height, areas, physical aspects of walls, pillars, roofs and foundations. How households are spatially organized inside, outside and between them. What are the predominant construction methods used to build the dwellings, to try to estimate usage and waste during construction and demolition phases?
- **Infrastructure –>** Service roads and pathways (wideness, stairways, obstacles, physical characteristics, distance (personal metabolic energy) escape routes, drainage), energy infrastructure (wiring, poles, transformers) and consumption, water infrastructure (mains, reservoirs, wells, pumps, connections, installations) and consumption, wastewater

infrastructure (sewage collections systems, installations such as septic tanks), solid wastes infrastructure, generation (separation habits, possibilities of recycling) and disposal .

- **Spatial observations –>** 2d GIS data can be used to estimate current and past occupied area and can also be used to predict possible expansion areas over time. Remote sensing can be used to recognize patterns and try to identify construction typologies and even try to count households and areas of infrastructure. This approach is very useful to differentiate the formal from the informal areas, and also to support the classification of the different types of IUS's. Are the informal settlements of the city spatially comparable to each other? And between different cities? - Merging the 2d data with estimates of materials quantification per area resulted from the sampling survey, it can be provided with a 3d analysis. If interesting results are achieved these techniques can be also useful for scaling or extrapolation of the data to other regions.
- **Technical observations –>** Detection of materials being re-used. Is there any sort of previously discarded material being used for dwelling constructions or to replace absent infrastructure? Demolition and renovations waste: where they are being discarded? Could they be reused? What about recycling possibilities? Are there any common spaces in the community areas present? Are they considered in the calculations (e.g. squares, sports terrains, illegal waste dumping)? Are they being used? Is there any sort of green areas and spread vegetation? Is there any local management of resources? Are they organized or "randomly" done? If present, can the community leadership be considered influential?
- **Model-focused observations –>** The model to analyse different sorts of future scenarios will have to include the main drives of the informal settlement metabolism. These can be related to personal choices, habits and decisions of the considered households (that will need categorization), but also to the local availability of resources, services and technologies. The detection and classification of the drives will have to be looked for in the empirical observations but will be of great importance if there is the possibility that they can be inferred from the survey and the questionnaire applied to the pilot research areas.

Gaps to be tackled by the proposed methodology, derived from the major scope of the research which is the development of the methodology itself:

A. Tackle the present significant data gap of the field, generating new primary data by collecting it on-site by the observations of the researcher, established partnerships and local residents as sources of information. Materials will be directly analysed and accessed.
B. Detect drives and consequences of the inequality, unbalances observed – Qualitative analysis. Identify key points for interventions and policies to improve IUS and its relation to the city
C. Resource flows are always changing. In the case of informal settlements, they still unknown. Elaborate on future scenarios of IUS infrastructure reconfigurations and present infrastructural inequality.

3. Research Methodology

This chapter describes the relevant research topics, research questions, objectives, steps and study details. The frameworks used and data interpretations over a pilot research are also presented to support the discussion around a proposal a mixed-methods methodology to be adapted for future research.

Three main areas are defined and considered to constitute the research scope:

- *Materials Stocks and Flows Analysis*: The application of the method for a quantitative analysis directed at measuring (and estimates) for a better understanding the stocks and flows of construction materials in informal urban settlements, including edifications and public infrastructure.

- *Metabolic Configurations and Resource Use*: The application of qualitative methods and theoretical concepts, towards understanding drivers and details of the physical metabolism of informal urban settlements, focused on resource use and access and its infrastructural limitations and framed in four main elements: Energy, Water, Wastewater and Solid Wastes.

- *Infrastructural Deficiencies and Adaptations*: Reaching beyond the technical metabolic aspects, the infrastructure inequality and its realities, can be mapped, accessed and described to its complexity by qualitative analysis. What are the similarities and contrasts with formal areas?

3.1. Questions and Aims

Given these points and considering the gaps previously identified in the literature review conclusions (section 2.9), specific research questions and objectives were formulated to address two main gaps: the considerable lack and uneven distribution and of urban metabolism studies in informal areas and to provide an alternative to the urgent necessity of a viable bottom-up, by developing an urban metabolism specific methodology to be used to assess informal urban settlements resource use.

In respect to the Urban Metabolism of Informal Urban Settlements, this Project aims to address main research questions:

(1) *Is there a way to quantify the stocks and flows of construction materials present in the infrastructural built environment of the informal settlements using a MFA?*
(2) *What is the current state of resource access in the informal settlements? How to identify the drivers of consumption and infrastructural limitations? How to capture these aspects?*
(3) *Is the secondary data available coherent to the context found in "reality" (primary data)? Would it be scalable towards the city and regional levels?*

To achieve answers to each of the research questions four well defined main objectives are presented:

1. Propose and discuss an approach for a bottom-up MFA of an informal urban settlement. To elaborate the methodology, following a preliminary analysis through a pilot research which

included an on-site with participant observations and some data collection. Present the necessary variables and parameters.
2. Explore the expansion possibilities and steps to propose ideas to roughly scale the preliminary results with the support of the use of secondary and spatial data.
3. Investigate and raise the characteristics and interactions between local infrastructure and resources use on the four main elements observed: Energy, Water, Wastewater and Solid Wastes. This should be achieved by utilizing participant observations.
4. Compare and discuss the differences between the findings of the research done on the ground and the Census data.

Therefore, the main aim of this project is to perform a preliminary assessment of an Urban Metabolism of Informal Urban Settlements, utilizing the available secondary data and also undertaking research on ground level, at a pre-selected area within Rio de Janeiro. To further contribute to the field, a discussion on a method for analysing the metabolism of informal urban settlements, followed by a prospective in site analysis, and a full methodology outline is presented. This is a mixed methods approach where collecting primary data is necessary could provide the much necessary deeper understanding of different informal regions which then can be compared and new insights learned.

3.2. Methodology

Throughout this chapter, the rationale behind the methodology proposed is presented with all steps described, composing the set of observations and resources that are found useful to compose the methodology and justify the choices made by the present researcher. The methodology is firstly presented at the broader level and the steps to fulfil the above cited objectives are described in separated sections, narrowing it down using the information acquired in the pilot research with is then thoroughly reported. Furthermore, the Appendix A includes the visual registration and commentary on the findings related to the visit to the site that composed the pilot research.

This major scope of the methodology proposed to enable for an Urban Metabolism Analysis of Informal Urban Settlements consists, as represented in Figure 10, in the four following steps:

1. The 1st step is the pilot research definition in the target region urban metabolism assessment. The example area is defined and secondary data is collected and other definitions on possible limitations of access are presented.

2. The 2nd step is to be constituted by the series of visits done on site, composing a field-work research, divided into two major phases that could be done together. This is primordial to the method and aims to generate valuable primary data regarding the selected informal settlement and provides the foundation for the next steps.

3. The 3rd step is the analysis itself, starting by a qualitative analysis that includes the participatory observations and resident's interviews, comprehending infrastructure configurations and on-site investigations that have direct influence over the assumptions made for the quantitative part of the method.

The results of the data collection will feed a quantitative MFA of the material stocks and flows present in the selected settlement. The last part of the analysis is projected to be made is the exploration of comparison and scaling possibilities. This step can be done in parallel with the first steps as it involves statistically comparing and correlating variables that can be found in the secondary data database.

4. The 4th step of the methodology is the exploration of comparison and scaling possibilities. This step can be done in parallel with the first steps as it involves statistically comparing and correlating variables that can be found in the secondary data database.

   As a final outcome of the application of the methodology developed (which was not fully implemented for the present work) it is suggested that the results are reviewed, analysed and linked to literature, to generate an overview of the possible research development and outcomes once the methodology is fully applied. Observing lessons provided by the pilot research and a comprehensive description of the findings, relevant to some sustainability and equality aspects and recommendations.

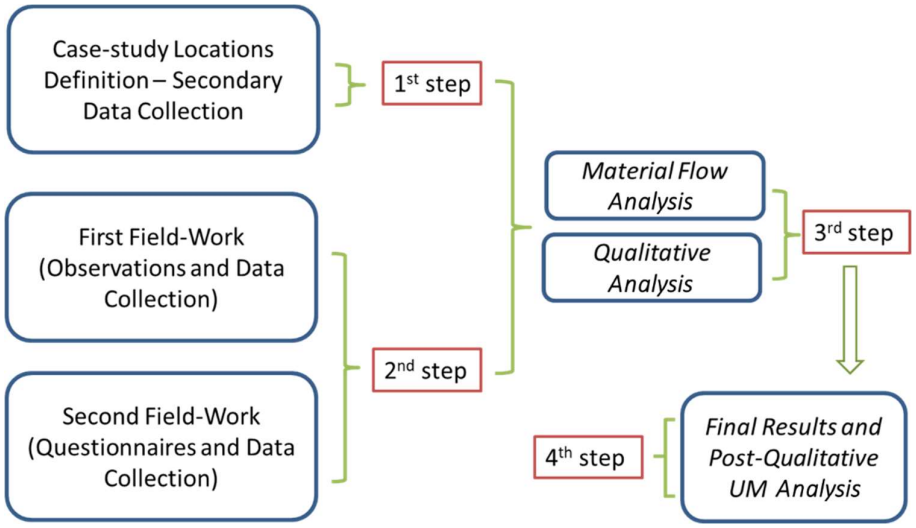

Figure 10 – The prospective 4 research steps that constitute the fully developed methodology, which was not fully implemented in the pilot research.

3.2.1. Defining the approaches and shaping methods

It's necessary to first elaborate on the necessary data and variables to support the methodology proposal. The first assessment done on the field will focus, but won't be restricted to the present infrastructure characteristics and configurations, and the levels of the access to resources and basic services:

- *Construction Materials, Stocks and Flows – Urban public and private infrastructure configurations. Sampling of dwellings, measuring and quantification of construction materials used. Construction processes (Heterogeneity). The aim is to define predominant dwellings typologies. Land use differentiations (Limits of Formal x Informal –> Hybridity of the Interface).*

- *Basic Services – Resources Access: Energy and Basic Sanitation (split into Water, Wastewater and Solid Wastes); Provision: access, public infrastructure and quality of the services. Drivers of consumption and habits investigation.*

Dwellings and Infrastructure need to be arranged in different categories with specific characteristics. For the quantification, the data should be analysed with statical models, an equation that represent a unique snapshot in time. The materials design, configurations, intensities data may be previously available in the state-of-the-art studies of the constructions and ethnographic or qualitative studies may have presented reliable case-to-case data. If not, these constructions are not complex structures and on-site inspections and observations should be enough to compose a base for the quantification of desired variables.

The proposed methodology is composed of a mixed-methods approach resulting in a triangulation of methods composed by the following three part that sustain each other as presented in Figure 11; [I – Quali to quantitative] Participant observations; [II – Quantitative] Material flow analysis supported by the use of secondary data, questionnaires and participant observations and qualitative methods, [III - Qualitative] Semi-structured interviews and analysis

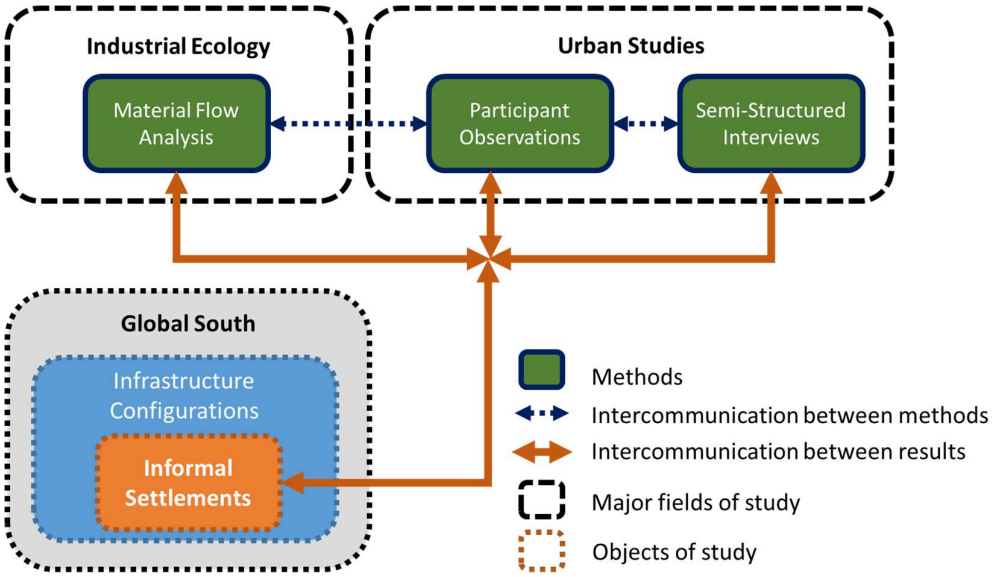

Figure 11 – Major scope, field overviews and the triangulation (interaction) between chosen methods.[1]

Table 3 represents how the different methods are all included in the scope and they are explained in the following paragraphs. The desired observations as a whole can be categorized in the main five

[1] The qualitative methods adopted are explained in the methods section.

major areas and its specificities on necessary data focus, as follows the central column in Table 3. The right column points which approach will provide grounds for the analysis.

I. Participant Observations **[PO]** done by the researcher at ground level by exploring the different areas of the informal settlement on foot. PO is appropriate for collecting data of objects and behaviours in their usual context. Slowly roaming the different pathways that connect the dwellings and areas of the community until all the community is considered covered. Three different steps form the basis of the intended approach:

[1] Establishing the connection – As being "accepted" in the community, where the researcher will strive to fit into the observed spaces and blend within individuals without being noticed as an unwanted presence to avoid interferences or biased conversations.

[2] Recording the observations – reflections and relevant data that goes along with it, in a series of reflections. This will include the descriptions, events that happened, conversations and what else was observed and captured. When notes are taken quickly and if necessary, discreetly, this must be done as soon as possible so in this way memory of details tend not to be fading away. Both qualitative and quantitative[2] data will derive from the observations, hence the importance of being clear with any assumptions made and to which parts of the analyses the data is directed to (Beloin St Pierre et al., 2017). Interviews should be coded.

[3] Analysing the data – Data needs to be organized to be presented, discussed and if necessary visually presented through graphs and thematic maps. Qualitative data derived from it will be used on the MFA on Public Infrastructure and needs to be adapted to the quantifications from direct visual observations[2] (Examples: Houses under construction, types of materials, apparent conservation state of houses[3]). Qualitative observations can be presented and expanded as narratives and also be organized by themes, such as: [Individual behaviour observed; individual opinions/facts; dwellings; pathways; water, wastewater and energy infrastructures[3]]. It's important to draw a clear line between what are observations and what are the interpretations based on them.

Informal conversations and interviews can be naturally incorporated into the activity however the focus of the PO is towards the built environment including:

- To identify and assess the public infrastructure present, the material constitution of them. Explore and map all the pathways, the distribution of dwellings and outside facade materials by walking and registering the observations. Examine specific material constitutions, a specific construction method or specific activities during the construction processes.
- Describe and detect potential participants for interviews, especially in purposive situations, such as a dwelling presenting a characteristic which is desired to know more details, such as:

[2] Quantifying the observations, counting, and also making assumptions. Examples: Observe the number of light poles, sewage installations, meters, wiring, pathways lengths and other observations that will include assumptions as some cannot be physically measured.

[3] Quantifying the qualitative observations, like, houses under construction (1 for foundation stages; 5 for "almost" ready, example: Roof already in place, walls up); type of materials (low, medium, high consumption); binaural observations as conservation status of houses and pathways (1 being good, 5 being - apparent risks involved) …

or environmental concerns observed such as visible wastewater being disposed of, water leaks, garbage disposals and etc.

- Reflections on questions for semi-structured comprehensive interviews with questionnaires to access what infrastructure configurations are present in informal settlements to attend these four main elements, and how do these influence the dynamics of resource access and use.

II. Visits to the dwellings of local residents, taking measurements and applying the close-end part of the set of questions that are aimed towards quantitative analysis of the stocks in the informal settlement. **[MFA-MQ – Measurements and Questionnaires]**

III. Semi-Structured Interviews, accompanied by the application of a questionnaire, composed of open-ended questions, focused on understanding the constructive processes, its characteristics, limitations and temporal aspects, composing a qualitative analysis on the infrastructural inequality present **[QSSI – Qualitative Semi-Structured Interviews]**

These three pillars are analysed along a secondary database and findings **[SD – Secondary Data]**. **[GIS] Mapping** can be used to quantify areas, support the sampling process and visually present some of the data collected. Overall the findings can also be supported by **specialist's interviews [SI]** with stakeholders, and specialists in academia or local residents and workers that are treated as specialists in the constructive process in the community.

Table 3 - Observations to be collected/generated at the development of the 2nd Step of the research

Area	Observation Data Focus	How it should be assessed
1. Infrastructure + Materials Constitution	Roads, sidewalks, pathways, alleys, poles, networks, wiring and smaller components such as meters. Public areas, parks, squares.	**PO + GIS**
2. Dwellings Specifications and Typologies	Buildings materials, descriptions, varieties, quantities, installations present and spatial configurations. Define the typologies of dwellings. How long, when, how and by whom and the dwellings were constructed? Are there apparent divisions of "typologies" areas in the settlement?	**MFA-MQ + QSSI + GIS + SD**
3. Energy (Electricity + Gas)	Is it available? Provided by who? Connected to the formal network? Is it metered and paid? How reliable? What other sources of energy are used (generators, batteries, gas, wood)? Identify when possible major drivers of energy use.	**PO + MFA-MQ + QSSI + SD + SI**
4. Water	Is it provided? Provided by who? Private access? Connected to the formal network? Is it metered and paid? How reliable? What other sources are used (rain, wells, lakes)? Are there any risks to health and environment involved in the access?	**PO + MFA-MQ + QSSI + SD**
	Are drainage systems present? Formal or informal? Flooding or landslide issues related to the occupation or lack of infrastructure?	**PO + SI**
5. Wastewater	How is it managed? Is it connected to the formal network? If not, are there septic tanks or any other form of treatment?	**PO + MFA-MQ + QSSI + SD + SI**
	If not, where is it discarded? Streams or public lands? Are there any risks to health and environment involved?	**PO + SI**
6. Solid Wastes	Is it formally collected? By who? Legally or not? If not, how and where is it disposed? Are there waste disposal / dumping sites?	**PO + MFA-MQ + QSSI**
	What is recycled (and leaves the system)? What is reused? What stays in the system? Any sort of separation?	**PO + SI**

3.2.2. Semi-Structured and In-depth Interviews

In-depth Semi-Structured Interviews is one of the most common qualitative methods. Their popularity is related to the human connection established in an interview. It gives the researcher a face, a physical presence, that when executed in a reasonable respectful manner, can also be a rewarding experience for participants and interviewers alike. Videos or audio of the conversations can be asked to be registered, supported by signed consent forms from all participants. The main reason for recording the conversations is that during the interview it is a complex procedure for the researcher to capture all the information disclosed, especially with the open-end questions where answers are not straight forward and some not even predictable, in a way that taking notes in parallel can be a complicated task. All this collected data should be coded in qualitative analysis program NVivo. Nvivo is a program that allows to code files into separate themes, references, text-tags, time-tags on sound or video files, permits also associate comments or transcriptions with the original audio files and also to identify

similarities, count words, words or expressions frequency, and other useful ways of making the qualitative interpretations clearer and organized.

The interviews would be the base of the interdisciplinary qualitative analysis towards understanding the dynamics of the urban metabolism on these contested spaces. As part of the interview, questionnaires (semi-structured but also with defined close-end questions) can be applied to residents of each the studied Informal Settlements to obtain complementary data that can't be obtained through the participant observation approaches, specially the interior of houses and the hidden elements of the constructions. This is a valuable part of the method proposal as the knowledge of materials quantities can often be described with a fair degree of trust, as many dwellers built their own houses, creating a situation where house owners will provide more accuracy than utilizing average constructions codes as used in other studies. This data will be used on the quantification of material stocks in-use flows (Example: Age of constructions can be derived from interviews as well; age of constructions has been used to define construction material flows in other studies: Fernandez, 2014; Brattebo et al., 2009; among others).

By organizing this data, to help visualization of the possibilities, and making clear assumptions over it, the aim is to define dwellings typologies. At this point of the research is not possible to estimate how heterogenic the dwellings will be and try to explicit now a number of typologies, would be only a guess. Nevertheless, studies usually focused on city use a single typology for whole neighbourhoods, even a single typology for residential x commercial.

Specialists interviews will depend if after the data collection, is considered that there is a lack of quality and robustness on some of the information obtained. In these situations, stakeholders and professionals of the field could be contacted to solve doubts, complement observations or raise important discussions, ad-hoc points of view.

3.2.3. Sampling Size

Sampling size on qualitative research is a controversial topic, as different authors argue that there is a strong subjectivity or not to sample size definition. This is reinforced that every research has its own questions, depth and time spent on each case, which may vary significantly. Saturation is considered the point (n=?) when the collected data starts to repeat itself with a very high frequency. Analysing 83 different qualitative studies, Marshall et al. (2015) showed that n=30 is a frequent desirable saturation point for samples, despite many of the studies simply not explaining why and how their sample sizes and/or saturation points were achieved. Considering that the sample size is more important to achieve quantitative representativeness and it is, in fact, necessary a bigger sample reaching close to two times this value. The qualitative part is also time consuming, so therefore if any obstacles arise, after reaching the proposed saturation point, the interviews can be done only to achieve the quantitative variables desired.

Three sampling methods are most commonly used for qualitative interviews. Purposive sampling is done when there is no target size of sample, but only based on specific characteristics, which is not the case of this research, in general, but can be, in specific situations (as this very specific example: During the first site visit it was exposed that there is this one resident that have its house walls made of crude clay, one of the very few that may last, this would be a case of purposive sampling) and observations such as these will be kept "on the radar". Quota sampling is similar, characteristics and criteria are defined, but also a target number for the sample size. The recruitment of new participants

is continued until the quota is achieved. This will be the actual approach chosen for this research method proposal. Up to 30 participants on the only selected criteria – Must be the dweller that is the owner, constructor and if responsible for the modifications of the space, construction materials acquisition and holds other relevant information about it. Therefore, in terms of the qualitative part of the interviews, 30 will be considered the target of an ideal sample size. If the data collection from 30 dwellings, in a best-case scenario, is easily achieved, purposive sampling comes into play, when the recruitment process could focus on auto-constructed spaces that still belong to original owners/constructors. This refers only to the application of the complete interview.

The sample size towards the quantitative analysis will have a target quota of at least 100 dwellings (for each 400 dwellings – 2010 Census) in a best-case scenario. Realistically, in a normal case scenario, this may not be achieved as it involves a time-consuming task of measurements. In parallel, snowball (chain-referral) sampling may be an interesting way of reaching new participants. In this approach, participants are selected not only by the selected criteria but, also within a recruitment strategy where participants or non-participants contacted in advance by the researcher refer and contact themselves, other potential participants based on their personal network. This is particularly useful as it can speed up recruitment processes and support the identification of more stand-out cases. In addition to that, it provides the potential participant with a perspective of how the interview is made by one of them.

This process, nevertheless can be reinforced using the connections and possibilities presented by the research assistants, as "locals". As explained before, these are not the type of urban spaces where random sampling is easily achievable. A small event to be realized on their common space (at the bottom at the community) along with some formal activity may be a useful strategy, to push further the possibilities of reaching larger sample sizes.

3.2.4. Developing a pilot research - Choosing a target Informal Urban Settlement

The project was motivated on a major global South view scope, on the necessity to explore the dynamics of the informal urban settlements of major cities of the developing world countries, limited to a specific pilot research. Based on the project scope, nationality and origins of the present researcher, Rio de Janeiro - Brazil was chosen as the city were the preliminary research will be realized. This choice is also reinforced by some relevant facts to the worldwide and local informal urban settlements scenario:

- Brazil has the 5th largest population of the world, and overcrowded urban areas including two of today megacities (São Paulo and Rio de Janeiro), with around 86% of the country population being urban. 6% of the total country population lives in IUS's, with 45% of these in the 15 biggest cities of the country, making them a constant presence in the cities fabric (IBGE, 2013).

- Rio de Janeiro, the formal capital, registers today the largest numbers. With 1,4 million people living in informal settlements, in a variety of levels of vulnerability, corresponding to a significant 22% of its total population. São Paulo has 1,3 million (11%), Salvador - BA, 0,9 million (33%) and Belem - PA, 0,75 million (54%) (IBGE, 2013).

Some social aspects of the research are relevant to the choice of the target areas and are here justified:

- Informal settlements, in general, are areas that pose challenges and risks. Some of them include residents in considerably vulnerable and unprivileged marginalized situations. Communication is also a barrier. Ethics must be considered as a priority, therefore the researchers must have reasonable access to the communities, either at a personal level or through partnerships with institutions that have "granted" permissions through contacting local residents and associations. These partnerships are detailed in the following section of this report.
- Violence, drug traffic and police conflicts are often present, limiting the possibilities of research being done freely throughout any of the numerous informal settlements distributed through the city. Restricting it to an area where all these variables are under control is a safety necessity, reinforcing the first point presented.
- It can be added that the choice of the areas, considers also that the necessity of renting accommodation or expensive transportation methods, such as renting a car, would limit the possibilities of the project even more, due to the necessity of higher amounts of funding.
- The researcher is a Portuguese native speaker providing the ideal opportunity to study this specific country on ground-level.
- It is out of the scope of the project to try to obtain a representative sample of all Rio de Janeiro Informal Urban Settlements, a universe with 785 '*favelas*' in the city alone, this can only be achieved scaling outcomes. The choice for one settlement is justified by the point of view that: It is necessary to dig deep into the characteristics of one area.

The Community of Beltrão (A), represented separately on the map in Figure 12, is an informal settlement localized in the city of Niteroi, in the Rio de Janeiro metropolitan area. In 2010, the Community of Beltrão had 1047 dwellers in 319 dwellings, resulting in 3,28 inhabitants on average (IBGE, 2013).

This area is selected to be where the part of the research preliminary pilot research. The preference for this area was related to a series of factors described below.

- Geographically, this informal settlement has its limits well defined and its walkable to its full extension through accessible pathways. It is a conglomeration of edifications on a hill slope, with no streets crossing through it, as it is typical of many of the settlements of the city (Pearlman, 2010; IBGE, 2013). The size of the area and number of dwellings present (319 in 2010), fit the conception of the project to perform the proposed methodology.
- In the social aspect, the researcher grew up and lived for more than 25 years in its family apartment localized not far from the settlement, at approximate 3.5 kilometres of distance, possessing knowledge of the whole region and having visited the specific area a few times during life. This was a major factor towards the concrete possibilities of establishing ideal partnerships with local residents and future collaborations.
- Inequality is high within the area, with Niteroi being the richest city of the country in income per capita (IBGE, 2018). Close suburbs to the community are wealthy and could present an interesting scenario for future comparisons and discussions about the infrastructural inequality.

Figure 12 - Community of Beltrão and its insertion on the Santa Rosa suburb in the city of Niterói, part of the Metropolitan region.[4]

3.2.5. Secondary Data sources

Considering the necessity of household level data, the best available source that it can be obtained is the National 2010 Census. A 2020 Census was scheduled to take part in August 2020, but it might be 3 years or more until the final releases of the results as cited by the own institution chronogram. Data results from Census can be contested, and present different methodologies that varies from year to year (the last one was in 2000 and it was fairly less comprehensive), but are seen as valuable public resources and should be used and disseminated with the objective to be of used by science and politics, as, many times, it is the one and the only source of information.[5]

The Census 2010 universe database is publicly available online, with several supporting documents describing its data acquisition process, general results, specific variables and spatial data. It is available by *censitary sectors*, which can be downloaded and extracted from .csv spreadsheets utilizing the censitary code to the corresponding areas to be accessed. This database provides a whole country large dataset of bottom-up collected household level data ranging from population, area, dwellings size, household configurations, dwellers age, race, sex, schooling, basic income among others numerous variables.

[5] The city council of Niterói, might have other data that is not available online. On its portal only the Census data was replicated. This stakeholder will be contacted once the field work starts and public information on the areas will be requested.

Community of Beltrão (A) comprises two censitary sectors Vectorised spatial data is also available for the location of informal settlements contained in the database, consisting in geographically referenced shapefiles (.shp or .kmz).

3.2.6. Material Flow-Analysis

To achieve the objective of assessing the Urban Metabolism of the Informal Settlements, an overview to serve as the basis to be expanded in details, of the accounting method for a Material Flow Analysis was outlined as represented in Figure 13. A MFA process may require large sets of data, therefore the quantifications on this project are not intended to be a fully accurate representation, but rather to provide a solid basis for capturing the levels of resource use intensity and drives throughout the system. The perception of, when applying the method on the ground, what variables are worth observing/calculating and what was not useful or hard to assimilate into the analysis, to enhance the method, is also one of the intended outcomes. This whole method is a proposal that can be enhanced, when, not only through the researcher (PO and analyses) but all the involved participants, provide their inputs. The method utilizes a bottom-up approach, where materials will be grouped in different categories and material intensities defined. A basic sensitivity analysis (exploring minimum and maximum values – using the error range assumed, Table 4) will be used to access the uncertainties and assumptions influences.

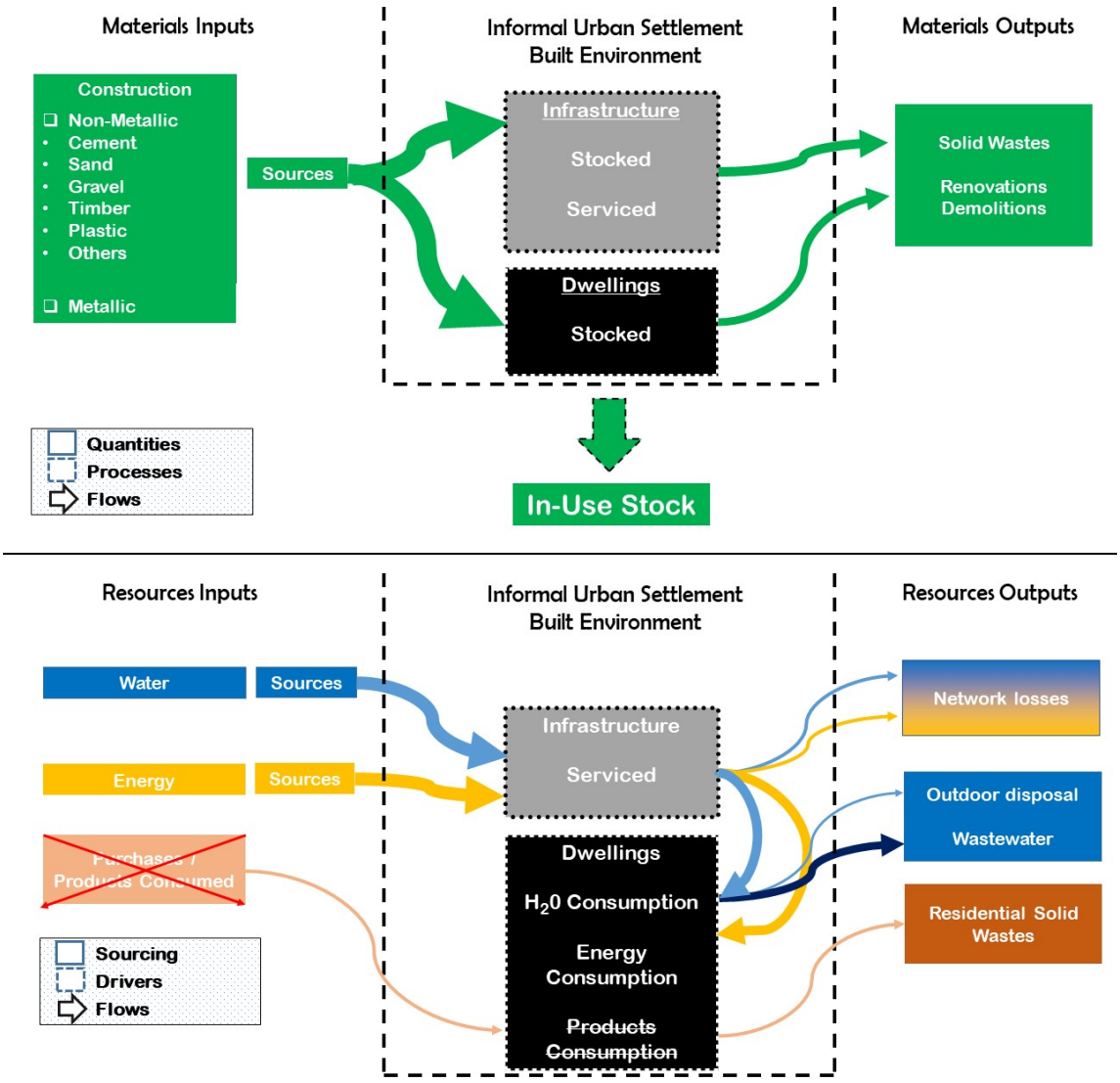

Figure 13 - The definition of the outline of the Informal Settlement system as: (a) its material stocks and flows; (b) aspects of the investigation on resource access (crossed objects are not included in the study).

In order to estimate the construction materials stocks and flows present in an informal urban settlement, different variables must be obtained. The method approach divides the quantification process into three major categories, each one containing its own steps, as follows:

I. Housing infrastructure and other edifications
II. Public access and service provision infrastructure
III. Construction materials flows
IV. Water, energy use (Qualitative flows)

I – To obtain the material stocks of the edifications in the area, first is needed to know how many edifications there are in the area of study and define a sample size to be collected. Authors arguments range from: [1] that there is no such thing as fully representative sample, even on quantitative studies,

as it would be valid only if all elements of the universe were sampled to [2] "a representative sample is one in which each and every member of the population has an equal and mutually exclusive chance of being selected". By this definition, no purposive sampling could ever be considered representative, and by different reasons presented here, a spatial randomized sampling would be impossible to achieve. This is recognized as a project limitation.

Utilizing the formula for normal distributions sampling, for when standard deviations are not known (Casella and Berger, 2001), assuming a 10% margin of error tolerance[6] and 90% confidence interval, results in 56 dwellings to sample. Therefore, the sample size selected (n^{min} = 60; n^{max}=75) can be classified as a large enough sample to provide basis for inferring reasonable generalizations, defining typologies, thus, justified by the complete lack of data about these specific characteristics that are planned to be observed in the literature up to date.

Table 4 – Sample Size parameters

Sample Sizes using the Normal distribution			
Margin of Error	10	%	Edifications configurations are not completely heterogenic, there is a degree of similarities that can admit a larger margin of error than 10%
Response distribution	50	%	Considered normal as the universe of answers is not known
Number of dwellings	319	Units	Total dwellings according to the Census 2010 data
Confidence Level	90	%	A confidence level of 90% for estimations on the scale of assumptions that are physically made is reasonable
Sample Size	56	Units	Resulting sample size (90% Confidence Level)
Higher CL (95%)	74	Units	-
Utopic CL (99%)	110	Units	-

The interviews will comprise the qualitative observations formerly cited and also the physical measurements of the spaces and objects (Instruments: Using two electronic measuring tapes to speed up the process, based on the pilot project experience). A series of quantitative variables will be asked when not possible, or not necessary, to measure (listed in Table 5). These elements will comprise the inventory of the constitution of the residential built environment of the area. Photographs will also accompany the measured spaces, utensils and another relevant aspect of the materiality of these spaces.

[6] It's hard to justify statically this choice. It seems more than reasonable to the level of analysis usually made on MFA/UM; when normally whenever data is available will be used without digging into uncertainties. Tanikawa et al. (2015) for example found from 20% to 35% just by comparing a GIS with a Prefecture-level data approach on a very same area.

Table 5 – Observations and measurements relevant to typologies definitions and the materials quantification inventory

Social Variables	Assumptions made
Number of dwellers	-
Number of floors	-
Number of rooms (Bedroom = BD; Kitchen = KT; Living Room = LR)	-
Separate Kitchen? (Y/N)	-
Number of toilets	-
Number of windows	Standardized size and materials
Number of doors	Standardized size and materials
Number of collums [1-12]	Hidden element - May rely only on residents indications
Floor Area Variables	
Floor area rooms [R1-5]	Rounded up to 0,1 m
Floor area toilets	Rounded up to 0,1 m
Total floor area	Rounded up to 0,1 m
Roof area (Concrete slab? Y/N)	Can't be measure precisely
Outside constructed area	Rounded up to 0,5 m
Linear variables	
Ceiling Height	Rounded up to 0,1 m - Inclination discarted if not significant
Total area of inside walls	Rounded up to 0,1 m
Total area of outside walls	Rounded up to 0,1 m
Height of pillars / collums	Rounded up to 0,1 m
Width and thicknesss of pillars	Rounded up to 0,1 m

Materials Assessment (Also specify type of trace and if metals are included (y/n)	Assumptions made
Rooms walls	Standardized materials and composition traces (Bricks, tiles, cement and concrete compositions)
Rooms floors	
Toilet walls	
Toilet floor	
Kitchen walls	
Roof	
Collumns	
Foundation	
Outside walls finishing	
Inner walls finishing	
Floors underbase	
Outside areas	
Windows	
Doors	
Water tanks	
Others	

After collecting the data, to quantify the edifications materials in use, first, it has to be determined predominant typologies of edifications. This cannot be defined *"a priori"* as it is heavily dependent on the variability, the heterogeneity, of the collected data. As cited before, despite belonging to the same income level/class, it is not reasonable to predict a certain number of typologies will be found/make sense. Three typologies could be considered already close to the ideal, as many studies utilize a single typology for whole neighbourhoods and even bigger areas when doing a material stock analysis at city or regional level. To achieve that, if a considerable variability is found, two different types of clustering analysis could be used and results pondered between them. Using dendrograms by applying an agglomerative hierarchical clustering or using often used algorithms such as k-mean, which has the drawback (or advantage) of having to select the number of classes in advance (both of these approaches will be used in the scaling step, so are better explained further ahead). This is a step that would need to be decided later as the universe of data still unknown and it's not worth guessing it at this point, as there is a possibility of only using simple: [max – min – averages – standard deviation parameters] may be enough to intentionally (manually) select typologies.

From this point, the predominant typologies of edifications will be the basis for considering the amounts of each considered material per unit, per m^2 or per m^3; these variables are typically called material intensities, and each element will be described (Example: Floors base, outside and inside finishing and aggregating mortar all use cement, but in different quantities and traces. These profound investigations and assumptions will be made only once predominant typologies are defined.

Once the typologies (TP_x – where x is the range of typologies) and its composing objects (o_y – where y is the range of objects) quantities (or dimensions) are described and defined, the quantification is done by the following the formula where a specific material stock (MS), of a specific material (i), in a specific point of time (t – assumed as present), is the total sum of the physical characteristics (V –

volume of the material), multiplied by its density (u), multiplied by its material intensity (MI) on the typologies classified, divided by the area (a) occupied by the typology, resulting in weight units (material stocks – MS). This will be done for every material considered in the dwelling and infrastructure typologies:

$$MI_{TPx}\left(i, o_y, t\right) = \left[V\left(i, o_y, t\right)\right] \times \left[u\left(i, o_y\right)\right] \times \left[\frac{1}{a_{TPx}}\right]$$

To sum in:

$$MI_{TPx}\left(i, t\right) = \sum MI_{TPx}\left(i, o_y, t\right)$$

Example: Material Intensity (MI – kg/m²) of cement (i) used on columns (o_y) on Typology 1 (x = 1; t = present) = Volume (i,o,t – m³) * Density (i,o – kg/m³) / Total area (m²) of Typology 1 = Total Kgs of (cement) per m² (TP1).

For the total material stock (MS) calculations, is not even necessary to go through the calculation of material intensities. The sum of all the material quantities of each object (o) that contains a certain material (i), multiplied by the total of dwellings represented by a certain typology (TPx) will give the final result. However, the material intensities are one of the "golden variables" of the MFA/UM analysis, as it is the base for any scaling or reproduction of the study.

$$MS\sum_{t}^{i} TPx \; = \sum [V\left(i, o_y, t\right) \times u\left(i, o_y\right)] \; \times \; D$$

Or:

$$MS\sum_{t}^{i} TPx \; = MI_{TPx}\left(i, t\right) \times D_a$$

Where D (integer units) stands for the total of dwellings associated with the respective typology in the informal settlement, or Da (m²) stands for the total area of dwellings attributed to the typology. Example: Total Material Stocks (MS) of cement (i) on Typology 1 (x = 1; o_y = columns; t = present) = The sum of each object [Material Intensity (i, o_y) * Volume (i, o_y) * Density (i, o_y)] = Total Kgs of cement (i). The total material stocks (MS) of a certain material (i) will be the sum of the stocks of all typologies (TPx):

$$MS_t^i = \sum MS_{TPx}$$

An example of these calculations and assumptions is done on the pilot project utilizing a single typology of one house that was visited and it's described on item 3.5 of this report.

II – To obtain the material stocks of the public infrastructure in the area, typologies will be also defined. Roads, stairways, pathways. They include other elements such as sidewalks and light and electricity poles. The typology, in this case, is defined by the unit of length, and several assumptions are made, as these structures are not easily physically measured. Mobile phones 3d measurements apps that use known objects such as an A4 sheet of paper, can be useful to help on these quantifications. In terms of special linearity of the infrastructure, it could be physically measured with the instruments, or by walking the distance coursed by the structures.

Example: A pathway typology – 0,05m depth (d) gravel (i) bed, 0,03m mortar, 1m width (w).

The pathway length (l) is 800m along the settlement.

$$MS_{i=}(d_i \times w_i \times l_i) \times u_i$$

Or:

$$MIL_{i=}(d_i \times w_i \times 1) \times u_i$$

Where MS_i is the total material stock of gravel along the whole pathway, and MIL_i is the material intensity per linear meter, that could be used to extend it to other similar pathways categorized as the same infrastructure typology. The same approach will be used for the case of roads, which would include also light poles, wires, sidewalks and other elements present as objects (o_y), adding to the same linear meter result.

Water pipes, drainage and sewage networks also need to have a defined typology by linear meter or area to be quantified. As the sewage network was found to be existent above the surface, it can be also estimated based on measurements of the stems (rough plastic or concrete) and passage boxes (concrete and metal covers) that are visible. If they are below the surface at some areas, stakeholders (sewage company) must be contacted to acquire the possible dimension of it.

III – To estimate the flows, which includes renovations, demolitions and material waste during constructions would have to be known, these could be roughly analysed on site if evidence arise. A typical simplification is just using an average of 5% waste of materials, and this approach can also be used. But, in reality these auto-construction processes can actually show different figures then the average as they are done in a slightly different situation, where money hardship is something taken into account, and, also the fact that the materials must be carried by hand, so construction waste put away end up being body energy wasted, on both ways, up and downwards. This is one of the reasons why the interviews include qualitative open-end questions about the construction process, and some questions will approach possible these aspects. What could be inferred from them? Also, future flows could be usually derived from their approximate age and expected lifetime of constructions, however, it's worth mentioning, these constructions don't tend to follow strict codes, neither are being constantly renovated as considered in some formal area studies (Brattebo et al., 2007).

Based on the statements above, the qualitative observations may also be able to capture changes that continue to happen over time and are not detectable through remote sensing or major scale studies. At least, past flows could be estimated with some information's that could be acquired from the residents such as: When the houses were constructed? How long it took to begin; to move in from the start of the construction? Have any expansions been done? Is the house considered to be finished? If these answers are enough to provide interesting points, in terms of, flows, edifications and infrastructure could be arranged into time-scales. An example: in the case of dwellings, it could be interesting to separate, in classes as such: dwellings constructed from 1980 to 1985; 1985 to 1990; and so on. It could be 3, 5, 10 years' intervals, it would depend on the quality and assurance of

answers. Other option to predict flows, is to try to understand the ongoing or planned expansions, and their frequency, although these are possibly variable as it depends on many other aspects such as if its horizontal growth relying on available terrain space, or if its vertical growth, as it a common expansion with houses with concrete slabs that are just "waiting" for the opportunity (financial, income enhancement or a new member of the family for example) to be expanded.

Flows of water, wastes and energy will not be quantified as its accuracy based on consumption habits is too subjective to provide reliable numbers. It would need proper meters installed to monitor the use. Therefore, these options are discarded. The quantitative assessment will be limited to "yes or no" questions on access to water, wastewater collection, solid wastes and energy. Typical individual values of the region could be used, just to provide a panorama. However, unmetered energy connections, for example, may have a greater influence in raising energy consumptions, than its influences on unmetered water connections? As we know that the dynamics on the informal settlements seem to be different, therefore, it would not be interesting to simply reproduce numbers here. Nevertheless, these flows will be extensively qualitatively assessed on a reflective basis towards the existence or not of network connections and its consequences over the metabolism as a whole. Has access to water and energy been different overtimes? What were the limitations? These are some of the qualitative observations that will support the flows analysis. [Refer to interview structure below; also some of these observations have been done during the pilot research] In terms of solid wastes, the available bins at the depot, can be measured in volume, investigate the frequency of the collection service. By doing this and comparing with the typical average (higher scale) per person generation of waste, would give an idea of how limited the depots are.

Intended open-end interview questions / observations for analysis of flows:

I. Dwellings Materials – The constitution of construction, materials varieties types and quality used, durability, the age of the constructions, built by whom (auto construction?), labour force, the frequency of renovations/expansions. Explore issues, drivers and stable situations.
II. Energy – General energy consumption habits, financial responsibility for consumption, installations, electrical appliances available, knowledge about efficiency and rational use. Reliability. The energy source, individual or communal. Explore issues present, drivers of changes and unstable situations.
III. Water – General water consumption habits, financial responsibility for consumption, sources, alternative sources if present, knowledge about efficiency and rational use. Reliability. Explore issues, drivers of changes and stable situations.
IV. Wastewater – Destination, responsibility and present consequences. Explore issues caused, drivers of changes and stable situations.
V. Solid Wastes – Separation, destination, reuse, recycling. Quality of service provided, reliability, issues.
VI. Urbanization and Government – Transportation form used, the frequency of beneficial urban modifications. Work, health and education conditions (Distances, level of informality involved, links to the formal city)
VII. Technologies and Adaptations – Primitive or advanced technologies used to solve infrastructure issues/limitations, Adaptations to the lack of services provided, level of connectivity to the formal networks.

To represent these relations between drivers, limitations and other interactions found through the qualitative analysis, an interesting approach that will be adopted is the use of causal loop diagrams. These are diagrams that can be classified as a system dynamics approach. It has been formerly used at population level to describe dynamics and drivers influencing certain social aspects (which in this project will be resource access and consumption as described in the last paragraph) and to explore causal interactions and feedback mechanism that can be included or simply divert across multiple subsystems. As a result, patterns can be visually explained and multiple data results can be used in a single analysis to understand complex social movements, such as the energy access social interactions as explored by Smit et al. (2019) in a South Africa informal settlement. Table 6 presents the main components of causal loop diagrams, which can expand through different levels of complexity. A simple example, on the energy access findings, can be checked at the pilot research section.

Table 6 - Casual Loops Diagrams constitution (Source: Smit et al., 2019; adapted from Brennan et al., 2015)

Term/symbol	Description
Variables or words	Quantitative or qualitative factors that can increase and/or decrease
Arrow or line	Indicate causal relationships of influence
Polarity (+)	Variables change in the same direction (both increase, both decrease)
Polarity (−)	Variables change in the opposite direction (one increases and the other decreases, or vice versa)
Feedback loop	Two or more variables in a causal sequence that "feeds back" to the original variable, completing a loop. There are two types of feedback loops: **Reinforcing loop or Positive feedback** In a reinforcing loop, the effect of an increase or decrease (growing or declining action) in a variable continues through the casual pathway and reinforces the increase or decrease in the initial variable, thus amplifying change. **Balancing loop or Negative feedback** Balancing loops seek stability or return to a specific target. In a balancing loop, the effect of changes in variables within the loop is to counteract or balance the direction of change. Rather than accelerating the direction of change (reinforcing loops), balancing loops tend to slow down the rate of change so that, in addition to counteracting the initial change, they also tend to push a system towards some stable goal.

3.2.7. Scaling Analysis

To explore the scaling possibilities of the results, the secondary data of the Census database will serve as a base for comparisons between indicators that have meaning on being compared between informal settlements (Scaling) and with informal settlements (Inequality assessment, comparing utilizing formal areas data from Condeixa et al. (2017) study. Comparisons between the formal and informal areas, which have more data available an accurate will also provide a very interesting base for discussions. A bottom-up study of the whole city excluding the informal settlements in Rio was done in 2016, and it will be the starting point towards the infrastructural inequality assessment, where the figures will be blended into the qualitative analysis to discuss the inequality drivers, and represent the great disparity in infrastructural investments in areas that are so closely located (Table 7).

Table 7 - Some possible up-scaling and comparing possibilities with outcomes and results.

Direct Comparing Possibilities		
Variable to be obtained in the study	Comparable to	Variable available
Material stocks per m² of constructed area	Condeixa (2017) - Rio; other studies on Latin America	Material stocks per m² of constructed area of formal areas by building type and administrative region
Material stocks per capita	Condeixa (2017); other studies on Latin America	Not available but can be easily calculated.
Direct Scaling Possibilities		
Material stocks per m² of constructed area	Other informal settlements	Utilize the Census [per capita and dwellings] and GIS analysis [for area]
Material stocks per dwelling		
Material stocks per capita		
Variables for investigating similarities / scaling compatibilities with other informal settlements		
Total dwellings in the informal settlement	Other informal settlements	Utilizing the Census data
Average persons per dwelling		
Average residents income		
Resource use access level		

Some indicators that are presented between the Census variables on informal settlements, can also be analysed, for comparisons and for scaling, examples: total dwellings, dwellings per m^2, average dwellings per house, predominant topography (flat areas, or hill occupations, which are less interesting for the case, but not excluded). This step can be done in parallel to the field observations, as it does not include inputs of the collected data.

Scaling can be done with analysis will start from surrounding settlements, that have a great probability of presenting similar numbers that may provide reasonable comparisons, moving further into buffers zones. For example, and specifically comparing with adjacent areas in the metropolitan area of Rio de Janeiro, where most of the informal settlements are located on the steep hills and visually resembles the informal settlement analysed in detail. These analyses can be explored further towards other national level cities, especially the ones located in the south-east region of Brazil, which includes Sao Paulo that have a similar level of Informal Settlements incidence (Figure 14).

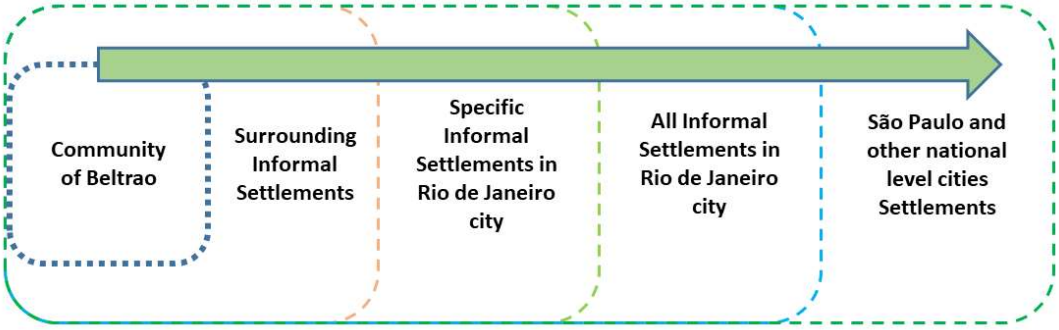

Figure 14 – Possible up-scaling buffering sequence.

The data collected should be processed in a database and presented described through maps, diagrams, charts, boxplots and other interest ways of presenting the relevant information together with the data collected on the other steps of the methodology. Alternatively, also tries clustering analysis of all informal settlements could be done if only a few variables are considered interested for the scaling analysis, expanding it towards the whole city, state and national level. Of course several assumptions will have to be made as, unfortunately, there is no secondary data on the materials constitution of the houses to be compared. One way or another, there is also a comparative analysis possible to do based on assumptions and observations that could be observed in situ, only by passing by some of the settlements that present social and size similarities, after the set of data is analysed.

Another interesting possibility is quantifying scenarios where whole communities or large groups of houses were, or are threatened to be removed and displaced. Using the same variables, such as number of dwellings, and trying to fit them into the developed typologies, could be a way to infer how much material was being removed and put away, and discuss a few environmental consequences of that, considering that demolition of these materials (cement, mineral binging materials, iron among others) which the production involves intensive energy and water inputs after such a short lifespan, despite being necessary sometimes, causes a considerable environmental impact. As it also involves the use of heavy and intense fuel consumption machinery such as backhoes, excavators, trucks. This is a relevant concept of the marginalization of informal settlements, for example the Community of Vila Autódromo, where 470 of 500 dwellings were demolished and families moved to apartments, in a very contested action as these families were there for more than 40 years and were removed just to make room and sugar-coat the surroundings of the Olympic Park, for the 2016 Olympics Games (Steinbrink, 2013; Gaffney, 2016).

3.2.8. A final Post-Quantitative Analysis

A number of post-qualitative analysis should derive from the application of the full method scope and analyses performed. Based on the literature of the field of Urban Studies and Informality:

I. What can be observed, described and discussed about the complexity of these urban spaces? How auto-construction and adaptations are influencing resource use?

II. Where the hybridity of formal and informal settlements lies? What differs these configurations from the formal settlements of its surroundings? Is it a splintered, unbundled urbanism fits the reality?
III. Can resource access define the social fabric of these connections? Is there a comprehensible heterogeneity of configurations beyond the formal networked city?
IV. Is the infrastructure contested? What are the limitations and drivers of (in)stability, at both community and individual level?

On a synergy constructed by the field-work experience and the academic knowledge on the metabolic configurations of informal urban settlements, its desired to expand the critical analysis towards:

- Where the communities struggle in infrastructural development? Where is inequality making its difference towards the universal provision of resource access?
- What lessons can be taken towards a common (regional x worldwide accepted) understanding of IUS's from this project? On the research findings, what are researchers missing to compose an integrated resource use framework to access urban spaces on global South cities, as it exists to the North?
- If the informal settlements where all upgraded to a "regular" infrastructure per capita / m^2, what would be the estimates on necessary inputs?
- What are the limitations to apply certain solutions to the present issues? Are they present at the individual, community or government level? Develop "What If" scenarios, where applicable. Could be these be the target of present policies? Or could be base for the development of new ones?
- What are the connections of the research to the UN Sustainable Development Goals? What insights and discussions can the project findings provide towards a better comprehension of how to achieve some of them, that are directly related to achieve equity and end infrastructure issues between less privileged countries, regions and/ or individuals? [SDG's 1-9-10-11-13 are directly related]

3.2.9. Recommendations for future work

Considering time and funding are available to fully apply the method, 4 topics are specified into deeper investigations around the research questions that guided this research. Topic 1 is an intended outcome of this work, but all these might be the target for 4 specific paper discussion at a future doctorate or research project level. Titles are approximate and are described to help define the paper objectives:

Topic 1 – ***The Urban Metabolism of Informal Settlements – An interdisciplinary review in a Brazilian Context*** – Framing the existing Methods in literatures, its limitations on data scarcity and the new method elaboration and the preliminary pilot research discussion;

Topic 2 – ***An Urban Metabolism Study of Rio de Janeiro Informal Settlements – A MFA analysis based on Construction Materials and Infrastructural Inequality*** – The sequel of the 1st paper, based on fieldwork data findings; papers 1 and 2 proposed here might be reviewed and conjugated into a single paper if its more interesting according to the project;

Topic 3 – ***Assessing Resource Use in Informal Urban Settlements – Next Steps Towards a Common Comprehensive Urban Metabolism Approach*** – What lessons could be learned in this direction, world widely speaking? Similar discussions have been done, by a couple of groups (Kovacic and Giampietro,

2015; Smit et al., 2017), but, what '*MY'* findings could contribute, especially considering the field-work phase and the focus on the built environment.

Topic 4 – ***The Favelas of Rio de Janeiro — A Discussion of Infrastructure Metabolic Re-Configurations of Informal Settlements and historical Infrastructural Inequality*** – The linking between the qualitative analysis, results and discussions, based on the Urban Studies literature. This paper will have a greater sense of writing if, based on the results and discussions, if the scaling analysis results are positive and reasonable. This is a bonus, and it might have a great value, therefore it could be published even after the thesis, if necessary.

Based on the findings and the deployment of the method on the ground, the enhancement of the method itself is also considered an outcome at this point.

3.2.10. Methodology scope limitations

A number of limitations are to be attributed to this research project. From the Census database, it was found that from a total of 317.000 censitary sectors of the country, 15.900, corresponding to 5% of the total, had been found to be part of the 6.239 identified subnormal agglomerates (informal urban settlements). Despite serving a valuable starting point for an urban metabolism approach for informal settlements in Brazil, this fact shows that if the whole country is considered, only an insignificant fraction of the total will be approached by this study, what is considered to be one of its principal limitations.

As there are not many references in the literature for Urban Metabolism analysis of Informal Settlements, the impossibility of comparisons to other similar research might be faced as a limitation. Nevertheless, the results to be found are directed to contribute towards a possible database that can serve as a comparative study for future research yet to be done, and provide insights for new methods, advancing the frontiers of knowledge on the field.

Representativeness of sampling will always be a problem within research in these areas, therefore, the researcher recommends caution when analysing the results in a general way, if by the end of this study, the scaling processes don't prove to be reasonable. Uncertainties are difficult to be accessed in some of the steps as it involves the direct participation of subjects in it, and as much as attention is taken at the preparation and when performing the interviews, there is not much that can be done to guarantee correct and honest answers, apart from trying to establish the best rapport possible with the community and participants.

Measuring interiors already occupied can be problematic on the presence of furniture such as wardrobes, and other limiting access pieces of furniture. This can raise errors in the utilization of the measuring instruments. All of the considered assumptions will be fully registered to be considered in the results. Sensitivity analysis can be an option to understand the impact of these assumptions and possible measuring errors. However, it is expected that the level of accuracy of the collected data might not be of the highest level, which is normal in the field of urban metabolism, figures are constantly approximated, rounded and estimated with assumptions in several of the methods, both top-down and even on bottom-up detailed studies with large datasets. Also, specific measurement

errors, as already considered a reasonable margin of error for the sampling, are going to be minimized through the adoption of the typologies itself.

3.3. Pilot Research Case – Community of Beltrão

To test some of the method procedures, a pilot study has been realized. This pilot study also served as the first approach and on-site incursion to one of the chosen study areas, the informal settlement, community of "Beltrão". This informal settlement is located in the suburb of Santa Rosa, in Niterói, the 3rd largest (IBGE, 2018) and 2nd most important city in the Rio de Janeiro metropolitan area (IBGE, 2013).

Figure 15 represents the area which comprises the selected region among other informal settlements highlighted. There is a similarity among all the informal settlements of this region, which is the fact that they are all located on hilltops, not flat areas, rendering possibilities of comparisons and increasing the representativeness of casual data exchange between the areas into the scaling analysis. This analysis of the other regions could be expanded, through the quantitative Census data and qualitative analysis – This is the first step into the proposed subsequent up-scaling analysis.

Figure 15 - Community of Beltrão in Niterói - RJ. The other polygons highlighted are also Informal Settlements.

The area of Beltrão Community comprises two sectors in the 2010 National Census. The area occupied, population and total of edifications are presented in Table 8. During the next step of the analysis, all the secondary data that is here presented will be compared to other informal settlements in the region.

Table 8 - Secondary data of the pilot project area

Morro Travessa do Beltrão - Niterói / RJ - Censo 2010 Data		
Perimeter	1,42	Km
Flat Area	86620	m2
Population	1047	persons
Total of edifications	319	units

According to the Census 2010 data (Table 9) the majority of dwellings are owned by its inhabitants (76%), which means they are not paying rent, but for the vast majority not necessarily means that they possess land titles of their homes, pay taxes or any sort of affirmably legal tenure, characteristics that have been found often in past studies. 20% pay rent, normally to formal local residents that left the community, or to local residents that have constructed a spare house, one as an investment, for rent and selling, or often upgraded to a better dwelling leaving the space for rent. 43% of the dwellings are occupied by only one or two persons. The average inhabitant per dwelling is 3,28. However, both of these number by themselves can't tell if it does or not represent overcrowd, as for this indicator it is necessary more than 3 persons per room. It is also significant to consider the actual average area (useful floor area) of these dwellings. This element could be investigated in the Community during the questionnaire phase.

Table 9 - Housing types, ownership status and level of crowdness in Beltrão Community

Dwellings type		
Houses	242	76%
Apartments	73	23%
*Error	4	1%
Owned and Paid	235	74%
Owned (Under Payment)	7	2%
Rent	65	20%
Given	12	4%

Total population	1047
Avarage inhabitants per dwelling	3,28

	Dwellings	%
1 dweller	66	21%
2 dwellers	70	22%
3 dwellers	72	23%
4 dwellers	53	17%
5 dwellers	31	10%
6 dwellers	14	4%
7 dwellers	7	2%
8 dwellers	2	1%
9 dwellers	2	1%
10+ dwellers	2	1%

Table 10 presents the secondary data on different resources use and access in the community. Each of these aspects will be discussed separately, to be commented along with considerations from findings derived from a household survey undertaken by the researcher, participatory observation and roughly defined semi-structured interviews.

Table 10 - Access to services indicators in the Beltrão Community.

Community of Beltrão - Niterói / RJ - Censo 2010 Data		
Variable	n	%
Total of dwellings	336	100%
*Collective dwellings	17	5,1%
Total of edifications	319	94,9%
Edifications under construction	8	3%
Energy Access		
With access to eletricity	319	100%
*With individual meter	269	84,3%
*With collective meter	14	4,4%
*Without meter	36	11,3%
Water Access		
With access to the water network	308	97%
With access to water by well	3	1%
With access to water by other source	8	3%
Solid Wastes Servicing		
With solid wastes collection	305	96%
*By municipal company	99	31%
*Collective depot	206	65%
Wastes burned at the property	9	3%
Wastewater Servicing		
With toilet at home	318	100%
*Connected to sewage network	224	70%
*Rudimentary cesspit	16	5%
*Drainage ditches / baresoil disposal	76	24%
No toilet at home	1	0%

In January, 2020, the present researcher went accompanied by a local friend to the community and during informal conversations collaborated with insights and helped clear some general doubts about what a participant observation on site could generate. The visit on-site was done based on Participant Observation Methods, where visual observations of the environment and its agents and objects interactions are intentionally described with a specific or open-ended aim. Four household semi-structured interviews with roughly defined questions served as a test to collect some quantitative data, characterizing a mixed method approach (Driscoll, 2007). In this case, observations were aimed at understanding the major possibilities presented at the Community, including diagnostics of some general and technical aspects of the built environment and resource access that could be assessed based on the skills of the researcher.

During the researcher's incursion on site, it could be noted that the lower part presents an urban situation closer to the formal areas. Some apartments and houses are located, at the base of the

Community, which is a formal street. Visible public infrastructure is present, electricity wires and poles, old asphalt and barely existent sidewalks and drainage system, however, they are present. When going uphill through some of the access pathways different situations occur and more elements of informality become apparent, the road ends after going up approximately 20-25 meters and from this point on, only different pathways, constructed and maintained by the own residents. At this point, there is already a visible lack of formal patterns of urbanization, which does not mean that there is not an informal way of self-organizing. These pathways will vary in width and takes people to and through different areas of the community. It is even possible to say that these paths present sometimes present some specific characteristics, being more or less developed than others. For instance, the path more to the right of the Community when facing leads to an area where there was a more critical situation of housing conditions, serious solid wastes issues, and a smell of evident sewage issues despite not clearly visible. At the top of the hill where the community is located, some of these pathways reach a gravel road, that reaches a dead end after coming from a distant neighbour towards the opposite side of the hill.

Figure 16 – The round perimeter pathway around Beltrão that was explored.

In 2010, the Census data registered 8 houses under construction. When present at the site in January 2019, the present researcher sighted only through walking across some of the pathways many more than 8 houses were observed being under construction or significant expansion. This fact shows that there is ongoing expansion in the number of dwellings, that should be further investigated to provide more resources to the historical analysis of the material flows on the mixed-methods approach. It is interesting to note, that the local residents were very talkative and demonstrated great knowledge about the evolution of the Community, indicating as found in other studies, that one of the most valuable sources of data for understanding the transformations that happens in these informal spaces. The local residents are the only one to know when who and by whom the constructions have started, finished and the progress of the construction. This fact is very relevant for the qualitative aspects of the analysis towards understanding the drivers and dynamics of the constructions processes over time.

Technically speaking, houses under vertical expansion or smaller horizontal expansions are examples of different observations that can`t be obtained easily remotely, or at a larger scale, it seems that only be done by bottom-up research on ground level. A remote sensing analysis/monitoring generally will focus on horizontal expansions. However, attached expansions (such as “terraced houses”) and vertical growth are harder to be captured by other than being at the place. The choice and justification for a mixed-methods approach pointed in a whole range of studies (Currie and Musango, 2016) starts to be clear in practice.

When confronting the participant observation findings with the secondary data complementary contradictions arise. Despite having individual meters in almost 85% of the residences, according to the Census data I was informed they do not pay for energy. Many of them are now simply shut off attached to poles, that serves for other wires pass through. Energy is obtained from the network at no cost. Residents mentioned that only one person pays the bills, and he supposedly also have an illegal connection, so the regular payments would not compromise all of its energy use. Situations such as these can be further explored, by communicating to other stakeholders as the energy distribution companies. Data available from 2014 estimates that the energy use in Informal Settlements can represent up to 35% of the total network losses registered in the Rio de Janeiro State (IBGE, 2013).

Kovacic and Giampietro (2017) argue, based on studies done by Achão and Schaeffer (2009) from 1997-2007, that the energy consumption of residential dwellings in informal settlements would be limited by the lack of possession of the residential electricity consumption devices on low-income households. This is justified by attributing favelas to an extreme poverty scenario, which most of the times is not the case, especially the favela of Vidigal analysed in their studies. Some “favelas” fall below lower middle-class levels of income, but higher than extreme poverty and even poverty in some areas. In addition to that, it was found that 100% of the houses had fridges and fans, 50% had electric showers and one in five had air conditioning appliances. In this visit, two of the four houses visited had air conditioners (which can be old and low maintained based on the non-responsibility for energy bills). This shift could be explained by the easier access to payments in instalments, and government tax reductions on important electric utensils such as fridge and washing machines.

Water access is provided by the municipal company at no cost to Community residents. Despite almost all houses being connected to the network, according to the secondary data, on the site the situation was different. The supply was deemed unreliable, partially intermittent by local residents. For some reason, the pressure of the water pipeline delivering at the base of the community is not enough to reach the higher regions houses. Therefore, a local self-obtained solution widely used by the residents is to install their own (or shared among a couple / few houses) hydraulic pumps connected directly to the municipal water pipelines, directing the water to plastic water-tanks and concrete water-cisterns. Cisterns are constructions that demand large quantities of cement and concrete making materials and can pose risks due to the accumulated weight they need to support when full. Nevertheless, they are often constructed at the more developed dwellings, motivated mainly by water shortage. During the Participant Observation, a specific case on the water access aspects could be observed. A senior man was fixing leaks in a very large plastic water tank located at a gravel road, at the very top of the Community. After being approached, he explained the situation. He was there servicing the water tank for a group of habitats of the higher areas of the hill (4-6 houses), which included himself. During summer, as they said, with water shortages, not even intermittently the water would reach their houses, so, they would buy water tank-trucks regularly to secure their water supply. It can be highlighted that this is an expensive, ineffective and environmentally impactful option to be used in an area that, actually, is surrounded by water networks reaching other houses and formal areas.

Solid wastes collection services are only present on the roads (formal street) on the bottom of the community. The dwellers must bring their garbage to large bins/small sheds localized near the community entrance, garbage depots. These structures were constructed by the local resident's association, less than a decade ago. In the past, the lower street of the community used to have a large quantity of garbage exposed. During the survey, some areas of the community had a considerable amount of trash accumulated on the pathways, between houses and over the local vegetation. It was mentioned to me that the community organized an action to close and clean the old illegal trash dump sites inside the Community, from there would be no collection and would spread disease proliferation and contamination. Today there is no single site of trash dumping, but it is noticeable that this does not stop some residents to continue to do it so "randomly", of course without incurring in any fines or persecution. This seems to be a lack of educational issue as it has the potential to cause problems to their own community, despite cited in several studies the presence of the "sense of community" in Rio informal settlements, which don`t comprise all residents (Pearlman, 2010).

Shifting from solid wastes to wastewater sanitation, according to 2010 data, 30% of dwellings were not connected to the sewage network and utilizes rudimentary pits or even worst direct disposal, which is a higher degree of deprivation of basic services being the cause itself or directed related to significant health complications (e.g. Waterborne diseases such as Cholera, Diphtheria) and environmental impacts. Considering the dryness of the days before the visit, in some places, residual water running from a few pipes and houses appeared to be open sewage. It seems that only "dark - water" (toilet) seem to be considered a problem. Grey-water from, showers, tanks and toilet sinks are frequently disposed of straight to the soil on outside areas. Although some concerning considerations, during the visit to the site, it was reported by the local residents, and also could be easily seen, that the municipal company recently installed new sewage pipes and connections. Collections stems are visible running through a great part of the centre-left side of the Community. Differently, from the majority of spaces, the connections are most of the time above the ground, facilitating estimates and detections of connections. It seems, at the perspective of the researcher, that at this point, the challenge resides on connecting all houses to the main stems.

The resulting Sankey diagrams for only single simplified typology is represented in Figure 17 and Figure 18 (A). 4 (B) shows a scenario with 3 typologies defined. Sankey diagrams are the ideal form of representation for quantitative aspects of material flow analysis and trace each flow and stocks retained, as detailed in the methodology.

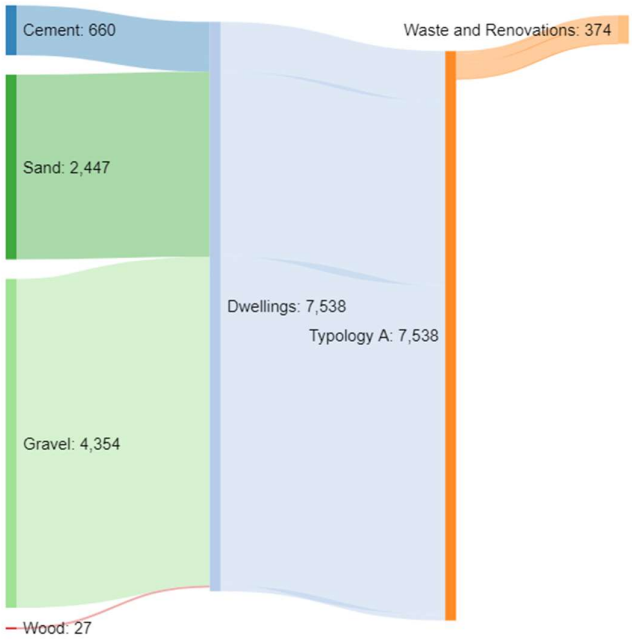

Figure 17- Material Stocks and Flows of the hypothetic scenario (Snapshot in time)

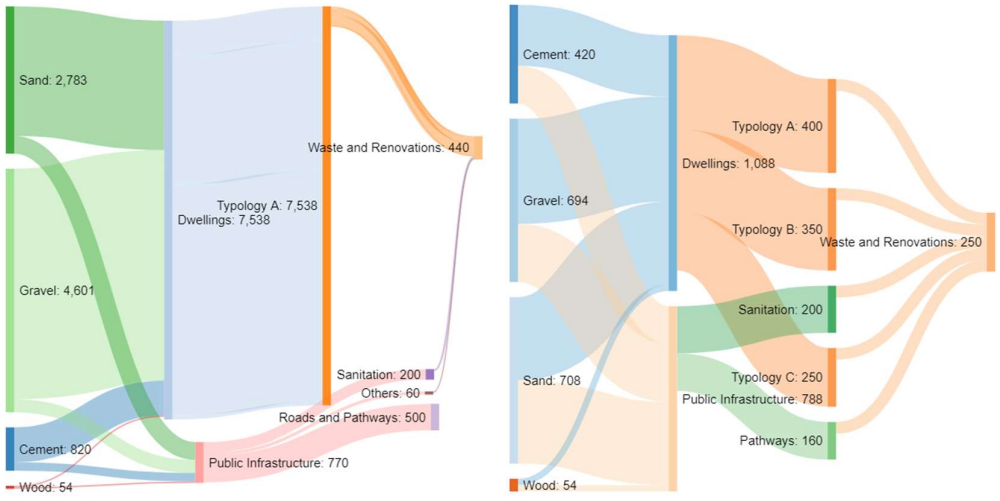

Figure 18- Material Stocks and Flows Sankey Diagrams: (B) – Same one, with added hypothetical public infrastructure numbers; And (C) – an example with a higher number of typologies.

In addition to the descriptive and investigative qualitative side of the research, a system dynamics approach using casual loop diagrams will be used to describe each category (energy, water, sewage,

solid wastes). Figure 19 represents the Energy Access Dynamics captured by the participant observation done in the pilot research. On the top, the positive feedback loop, is sustained by efficient registering, local inspections, and reliable service provision, and it starts when on the arrival of electricity to the community, more dwellings get interested to connect to the network, increasing the interest of the private company to provide a good and reliable service to customers. The negative feedback loop is influenced by the financial advantages of having electricity without paying. Therefore, it is derived from the lack of control and inspections or even the inefficiency of them. As discussed before, companies tend to include this as losses and repass the costs of paying customers of other formal areas and service quality is also prejudiced. Both of these have as consequences a higher "motivation" for paying users to migrate or add illegal connections to their dwellers. Other loops and loop elements could be included, for example, a loop analysing the scenario before infrastructure arrival, or a loop element of the encouragement of appliances acquisition as results of no bills to pay, or as a "free" energy rebound effect.

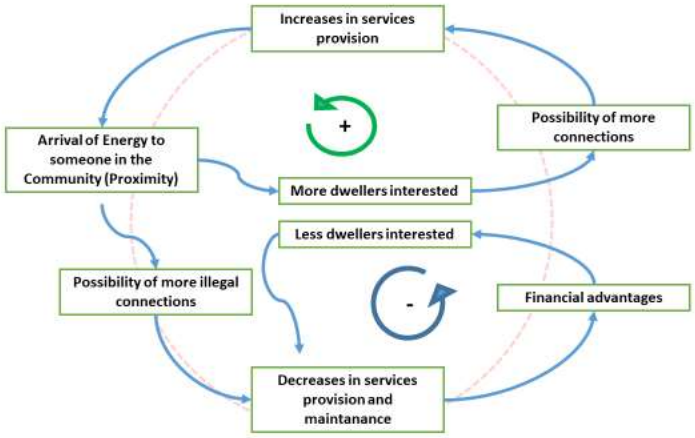

Figure 19 - Dynamics of the Energy Access in Beltrao Community using causal loop diagrams.

During the elaboration of this pilot project, it is also interesting to highlight that there are several studies done aiming at developing typologies for low-cost housing projects. However, it was not possible to find an article that studies specific characteristics, such as the area of edifications, and quantities of materials of the auto-constructed spaces of Rio de Janeiro informal settlements (including the term *Favela, also in the Portuguese language*. Predominant materials and qualitative descriptions of national and city level data are not present in the former Census IBGE, the National Institute of Geography and Statistics 2010, should be reached for information about the possibility of obtaining the sectored data, as it is only available at sub-district level, which varies from being parts of bigger suburbs, or multiple smaller suburbs in some cases.

This pilot project is intended to test the approach and possibilities of acquiring the variables on the field survey, visits and questionnaires application, which proved to be an extensive process, full of nuances on the contact to local residents, due to the mutual interests of both the researcher and local residents to tell their stories and a valuable set of other information's about the community. The speed of the process might be passive to be improved, but it certainly presents as it was done, expending between 20-30 minutes in each house, an achievable target (100 questionnaires in 50h of work). The interviews can be done faster if recorded to be analysed and coded later. Measurements can be sped up by using electronic measuring devices and training the research assistants and existing

volunteers if existent and able to help. More descriptions of findings are reported into the photographic storytelling reported into Appendix A.

4. Conclusion

This research aimed to development a methodology to enable the assessing of resource use of informal urban settlements utilizing a mixed-methods approach. In addition to a literature review of the field, a pilot research performed in-situ in a specific informal urban settlement was fundamental to achieve the main aim and primary objectives.

Summarizing the review chapter, it was demonstrated that the present methods in the urban metabolism literature provides a useful framework which is really useful to understand the materiality and flows of resource use in urban environments. The methods for accounting stocks and flows, specifically the MFA proposed in this research is in place to be used in contexts of reliable data availability or possibilities to quickly acquire them to support the analyses, rather than relying on city or national level data.

Answering the research questions presented, it is demonstrated that although there are major challenges to the fulfil the gaps and understand the urban metabolism of informal urban settlements, there are ways to achieve its major framework objectives of assessing resource use with the support of the present state of the body of scholarship of the field when adapted to the informal urban settlements context. Through proposing a mixed method composed of a Material Flow Analysis adapted to the informal urban settlements spatial and population realities this research contributes to the existing possibilities of the field and sheds light and hopefully will attract attention to these necessary analyses. The mathematical calculation steps, necessary variables to be measured, observed and achieved were listed, composing the quantitative part of the methodology, which is supported by Participant Observations and the outline of the Semi-Structured interviews which relate to the qualitative part of the analysis.

A pilot research to provide and test some of the research ideas and to explore the ways to address the research questions was done in an informal urban settlement in the state located in Rio de Janeiro, Brazil. The description and the representation of the location were presented, along with the most recent secondary data available being presented to the reader along with the methodology presentation.

In these contexts of real and alarming data scarcity, through reviewing the findings of the pilot research it was shown that the methodology proposed could contribute towards addressing this major knowledge gap which is the understanding and accounting of informal urban settlements and its infrastructural configurations and resource use. The methodology is considered to be deployable at ground level by researchers and other parts involved and provide valuable insights and increase the possibilities of quantifications of material stocks and capture the understanding of the drivers of resource flows. The outcomes of the proposed methodology could be then integrated themselves into major context / regions analyses, without the characteristics of these areas being overlooked as the literature review stated.

Results and evidence gathered in this research also indicates that Participant Observation approaches offers a useful and insightful connection between what the researcher can observe, interpret in order to be translated into quantitative analyses while also addressing and providing

possibilities for a necessary qualitative analysis which represents the non-static materiality and social side of the of the dynamics of these conglomerated regions. The data collection focus, variables and questions were outlined for each of the resource use areas observed and which of the approaches that compose the methodology could be directly related to each of them (Infrastructure, typologies, energy, water and both wastewater and solid wastes). The synergy between on-site observations and the existing knowledge provide the basis for the questions and insights described in a post-quantitative analysis which would be a reflective final step of the methodology.

Upon considering all facts, although there are limitations to what this methodology can achieve, it is not surprising that the primary data collection at ground level done in the pilot research, through participant observations and the direct interactions with local dwellers, provided a view where its concluded that there are strong limitations to the reliability of the secondary level data (in this case national / city Census level data), which was clearly observed into the energy consumption aspect. This reinforces the fact that for these areas secondary data should always be treated and considered with 'care' to avoid non-representative analyses.

Justified by of the intrinsic characteristics of these places, in some situations the presence of a researcher will be the differential to acquire reliable informative data that tends to be not provided to the governmental stakeholders. There are concerns about the legal status of the configurations of resource use or land use legislations, for example, which the researcher might be able to capture / identify as the pilot research confirmed.

While additional research (mainly the full implementation of the method into a region or group of settlements, achieving the ideal sample sizes and depth of analyses) is needed to prove this statement, the research also demonstrated that by utilizing methods as such the one presented in this work it is possible to achieve a more in depth understanding and provide great contributions towards local policy makers to develop solutions for the infrastructural problems existent within these areas which need specific solutions. To solve a problem, first there is a need to clearly visualize it. To visualize it is necessary to understand it first, and not leapfrog into attempts into applying solutions developed to formal areas, that may be incompatible.

The scaling of these analyses would demand confidence into the data collection and research outcomes of the methodology implementation that this project could not achieve. However, the clustering possibilities and possible sources for comparing and scaling at different levels were presented, which includes characteristics such as proximity, density, topography, predominant typologies and buffering zones. From the afore mentioned formal areas body of scholarship in the field, generalizations towards informal urban settlements could be useful, considering it would be unrealistic to imagine a scenario of unique understand of each of the informal urban settlements. Patterns and similarities are found among these areas just as they exist in formal areas, and this research aimed to contribute to the possibility of at least acknowledging and presenting outcomes that could confirm the existence of these similarities between these areas.

It's relevant to mention that dwellers of informal urban settlements often take the major brunt of deficient planning on city level, which in most cases are not their choices or direct responsibilities, but a simple consequence of the urban population expansion that still going through a recognized sharp ascent in most developing countries, reinforced through rural to urban migration as well as presented in the literature review.

In the light of this previously mentioned rapid expansion of these areas around the world, to sum up, it is clear that urgent action is needed to prevent more disastrous consequences to living standards of this significant part of the world population and also the environmental consequences of these

forms of occupation, which will not ‘disappear’ or be remediated by simply adapting solutions or relying on what the global North development has been for the past century. This is an important aspect that this research has addressed through its research questions.

It’s also the authors objective to provide reflections and raise concerns over the fact that the uneven distribution of the studies done to date are in urgent need of being diminished or overcame, bringing a more balanced view to what is really a ‘global’ context, in a way that these areas which are marginalized in overall governmental practices are not also left aside by the academia and the support the body of knowledge can provide to development.

To finalize, it is suggested that the reader explores the Appendix A (p. 83) of this research to be able to visualize understand a bit more of the specific contexts. Some of these observations, although they are not directly related to the objectives and methodology proposed in this research, they will provide an interesting report into the main areas addressed, to the reader. Captures what this vibrant community home to millions of hard working and passionate people as most of the informal regions of the developing world (even considering their disprivileged urban living standards and adverse social conditions).

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6. Appendix A

University of Sheffield - Geography Department

Adriano Ethur Dias – MPhil Prospective Analysis

Photographic Register of Participant Observations done to provide solid empiric bases to the thesis discussions

This is the visual communication section of the research. Visual results of the participatory observation are here registered. These photographs were obtained on the site visit to the Community of Beltrão, mid-January 2020 visits to establish the partnerships and perform the first local observations to fulfil the potential of research of the chosen settlement. This report presents several observations reinforced by the photographs that are relevant to the description of the present metabolism of the settlement.

The observations are presented organized into the five main aspects of the infrastructure, as discussed through the analysis. They are: construction materials and processes, energy, water, sewage and solid wastes aspects. Other observations related to the social influence of the metabolic configuration and infrastructure transformations and adaptations are listed in the last section.

Contents

6.1. Construction Materials and Processes

Figures 20a; 1b - Construction materials stored at the furthest point that a truck can reach in the informal settlement. From this point, materials are transported by hands to the locality of the construction.

Figures 21a; b; c; d – Local residents often transport the materials on their backs, to the construction/expansion of their own dwellings. The presence of many steps throughout the pathways limits the possible help of pushcarts to specific areas.

Figure 22 - Observe the hybridity of the formal infrastructure repairs done by the government after a landslide that killed 12 persons, merging directly into the informal houses. A couple of houses on an upper region are condemned and it was told to the researcher to still have residents in it.

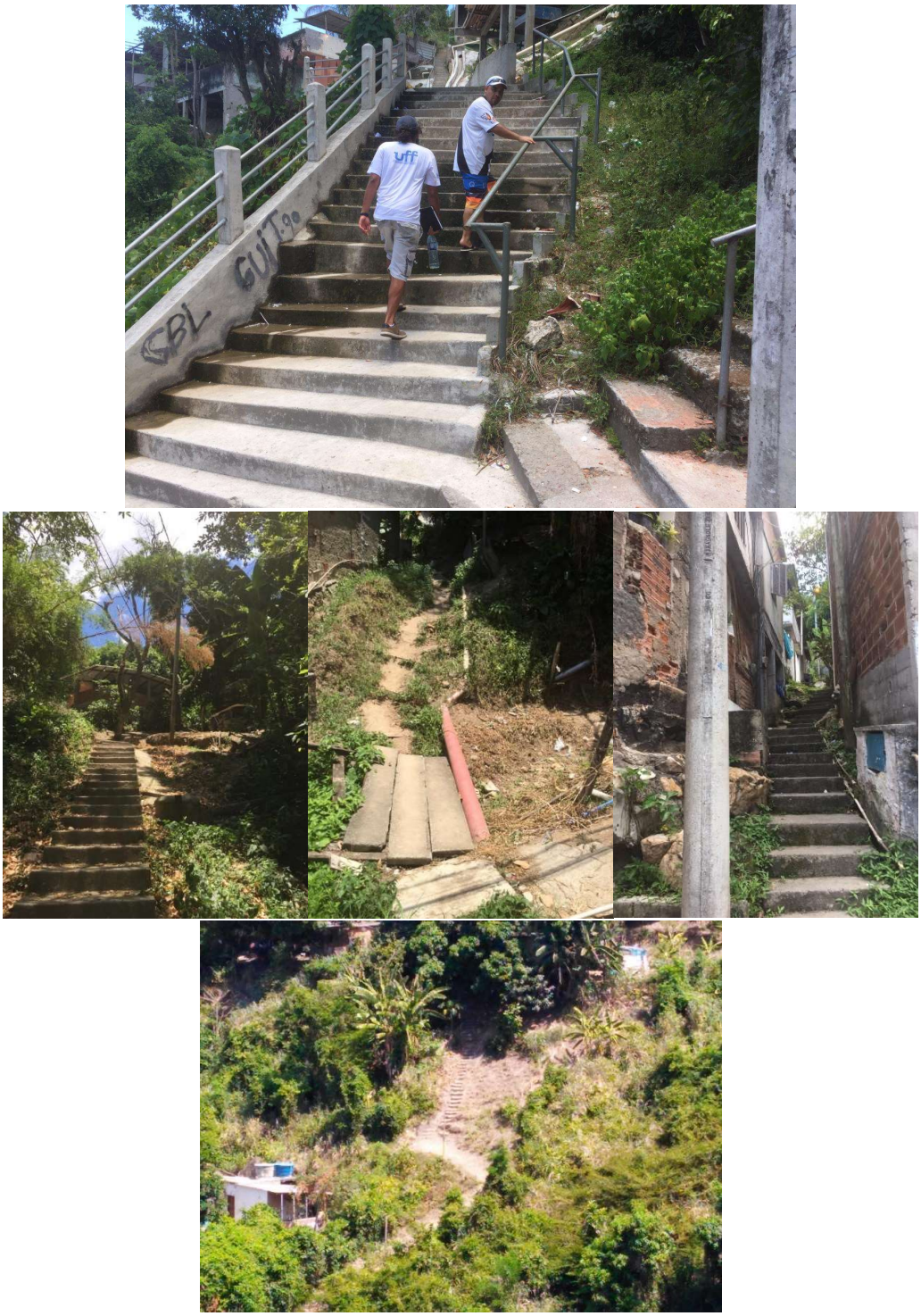


Figure 23a; b; c; d - Different pathways that are representations of the heterogeneity and the contest of the built environment among residents and the public power. Done by the city council (a; b), by residents (c; e) on bare land without a cemented pavement, and (d) done by residents in a more structured way using concrete and cement.

Figure 24 – Different courses of outside walls finishing side-by-side on the same geminated constructions. Even including exposed bricks, there seems to be no defined rule when it comes to considering a house as finished or not.

Figure 25 - An extension of the house under construction. According to the resident, it had to be given up, due to losing his job and getting into financial hardship. The construction materials have been stock in an improved way, creating risks for the surroundings and his own safety.

Figure 26 – Materials were also found stocked on a gravel road that reaches the highest point of the community. The road is not much used as it comes through another community (Zulu), with access from a different area. From here, materials can be carried down through the pathways, instead of upwards.

Figure 27 - On the back, a house that has been condemned by the state civil defence specialists. Residents still live in as evidenced by the clothes drying in daylight. Columns on the bottom that sustains it looks worryingly bent, and as it can be seen, the house is made of stones certainly adding too much weight to it. At this point Rafael, we were facing, and he was explaining where and how the house he lived went down on the landslide 10 years ago.

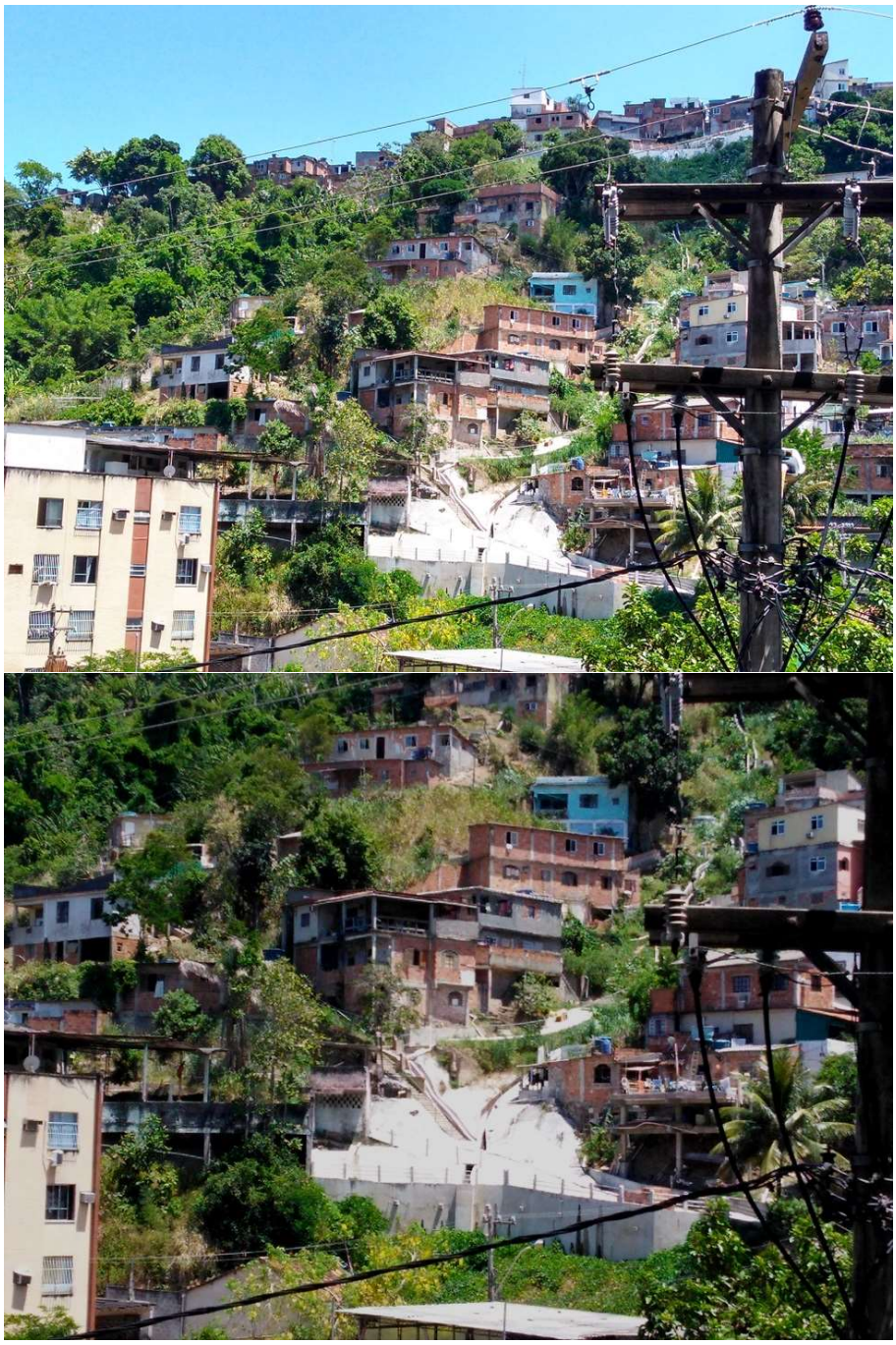


Figure 28 – View from a distant position of the area where the infrastructure works were done years after the fatal landslide occurred. As in this picture both the lower and upper-level works are visible.

Figure 29 – Fairly uneven construction observed to the right. Only a specialist to understand the risks it poses.

Figures 30 (a- d) – These older (a), newer (b) ceramic roof tiles and the zinc roof were seen on houses located side by side providing an element of heterogeneity. The fibrocement roof (d) as the cheapest option, is also apparently of common one on the dwellings.

Figure 31 – Some building pathologies are noticed as the construction processes, frequently lack quality control and can be even done in an auto-constructed auto-didactic way.

Figure 32 – The abundant rocks, apparently some sort of quartz, that occurs naturally in the hills of the community and are in this case sometimes seen in use. In this case, to sustain the foundation structure on some columns of this dwelling. It can also be observed the exposed pipe connections, water on the left, and sewage to the right connected to a junction box with the network.






Figures 33 (a – i) – Dwellings under constructions, on several different stages. Unfinished houses with unstable or abandoned elements are very common. An indicative of different temporal processes is the construction materials that can be seen stored in many "courtyards" showing different shades of oxidation that can vary based on how long they are exposed to weathering when not stored under a roof.

6.2. Water Provision and Network Observations

Figure 34a; b; c; d; e; f - Water infrastructure elements installed to the formal network of the water services providers (Águas de Niterói). The hydro-pumps (a; c) belong to the residents. The fragility of the superficially exposed system that connects the pumps to the dwellings is evident in the other pictures and it's possible to observe numerous repairs.

Figure 35 – Plastic water-tanks used by the majority of houses as their reservoirs. Old ones still use fibre ones. Plastic ones are preferred because of the better price, weight and ease of transportation. The second picture shows the hydro pump which belongs to the neighbour, and it fills his water-tank before reaching his. This dependency shifts a bit the water usage rates as he can`t rely on having his reservoir filled up as he wishes. A water pipe network connects it, and its located on the bottom of the settlement pumping water from the formal network.

Figure 36 - Water tanks and cisterns found with openings and clean water inside. The biggest risk is not only contamination of it, and the entrance of small animals. But also if they are still, leads to mosquito's proliferation, that causes dengue fever outbreaks that are common to happen in summer in many different areas of the city but have a higher incidence in informal areas.

Figure 37 – Next to the local resident that have a house under construction (a). He was the one that informed that the houses of this upper location do not have water reaching through the network. On the back, the 8000 litres water-tank that he was fixing the leaks and connections to receive the water-tank truck. This is a fair example of the sort of information that is impossible to be obtained without reaching the local residents.

6.3. Sewage Collection and Network Observations

Figure 38 - Recently installed network, the works were done only in 2017. New residents than have to connect their houses to the network themselves. It could be explored what are the obligations of the stakeholders in this case, and what are the limitations for the expansion and inspections of the sewage disposal in these places. The problems of being formally recognized or having or not land tenure rights, should not be an excuse for not dealing with the environmental problems that are happening independent of social or political disputes.

Figure 39 - On the days of the visit, it has been a while since last time rained. Some liquids that could be sewage or grey wastewater could be noticed in a few places of the community. In the cases shown in the pictures, they were adjacent to the sewage network, what could be leaks or not.

6.4. Energy Usage and Network Observations

Figures 40a; b; 12 - The vast presence of informal illegal energy connections throughout the whole community.

Figure 41 – Note the high rise columns, that are also often present and are done by local builders and construction workers. It is known that the risks are partially mitigated with super dimensioning of the elements such as the columns, pillars and beams in these situations.

Figure 42 - Old rusty energy meters. They are all over the place, besides the comments that no one paying energy. This element and its physical and temporal connections can be further explored in the research.

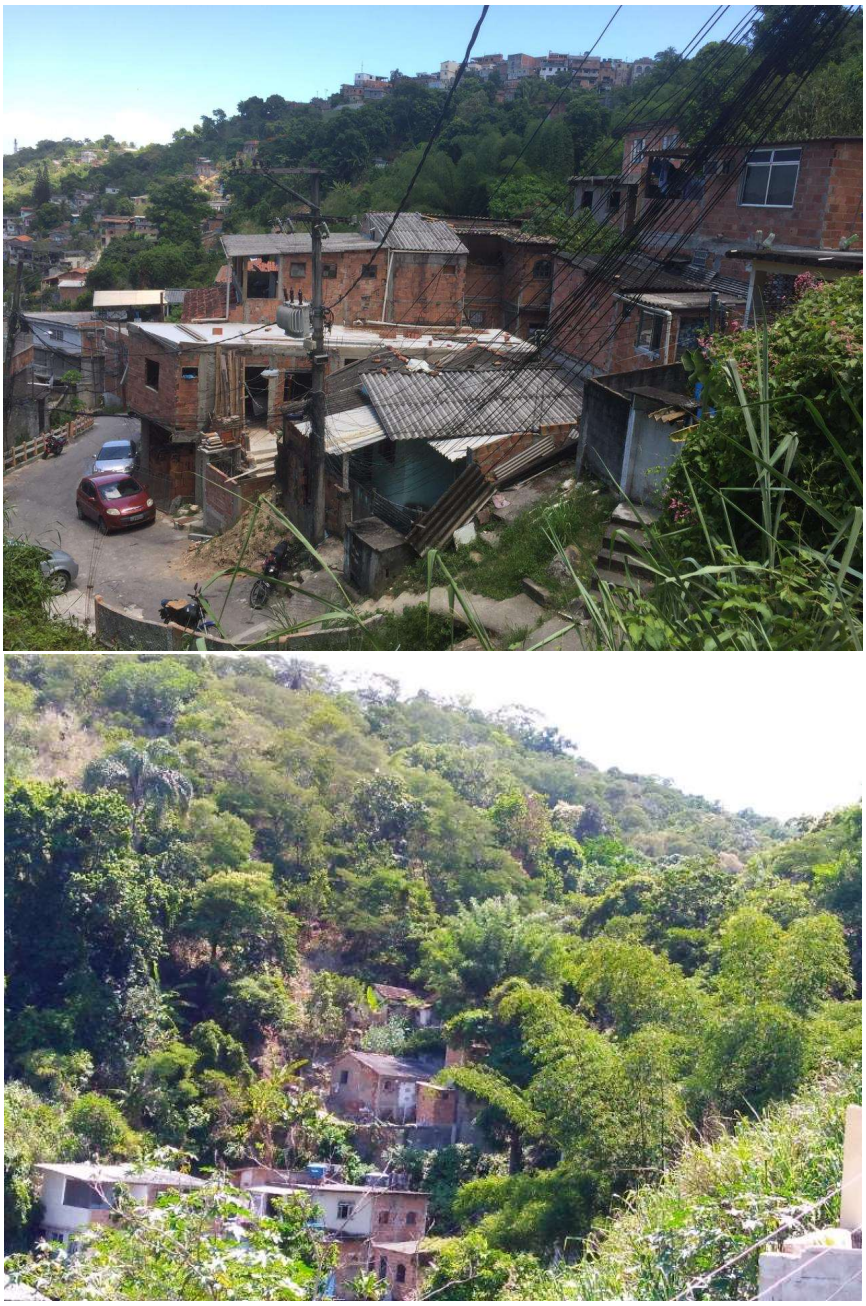


Figure 43 - Approximate limits of the formal x informal network of this space in the city. This is the highest energy company light pole, to the far right limits of the community. The second picture shows the same area, from distance.

6.5. Solid Wastes Disposal Observations

Figures 44 (a – f) – Solid wastes disposed into the environment and present also in the drainage galleries in the bottom (b, f), mostly, in this specific part, that follows one of the pathways of the community (e). It includes an accumulated garbage dump (d) that is reported to be set on fire occasionally.

Figure 45 - Garbage depot. As reported, not large enough to attend the whole community. There is no separation of waste. It consists of 11 barrels of (guessing) 400-500 litres and it was constructed approximately 9 years ago by the local resident's association.

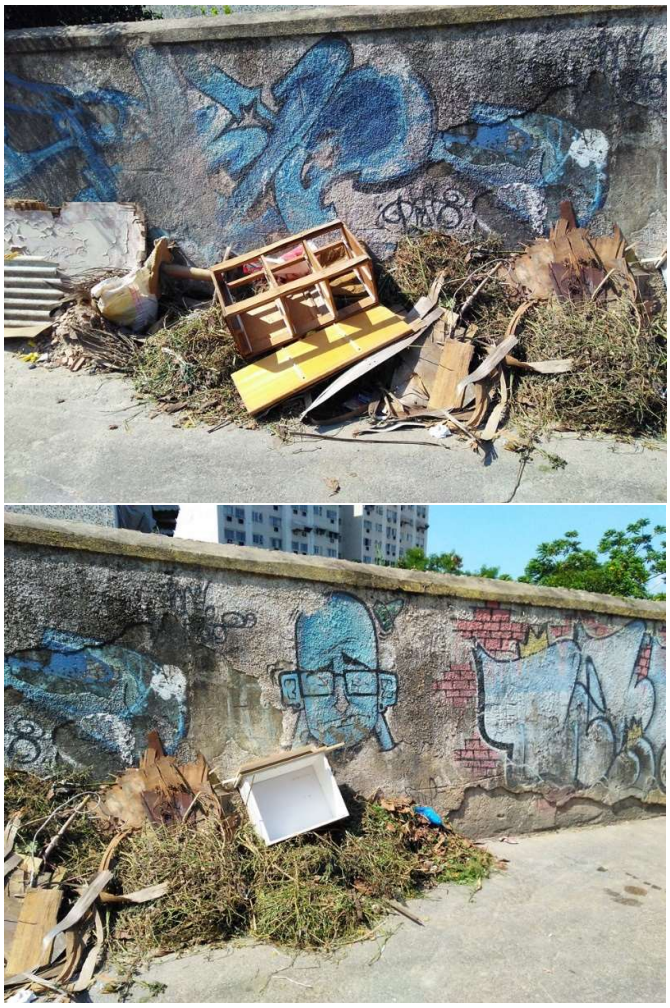
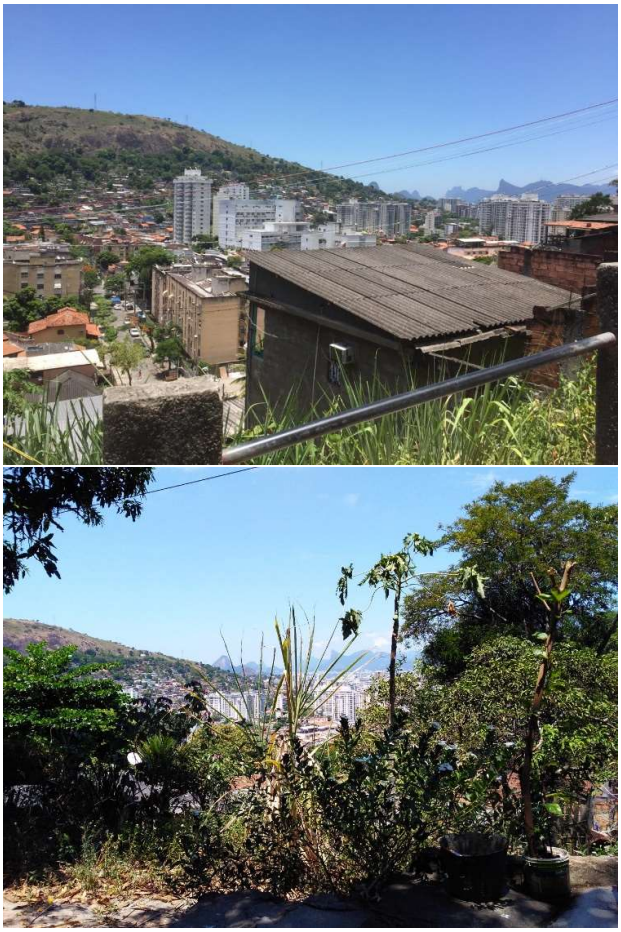


Figure 46 – Some bigger volume and green wastes were disposed in the street ground just in front of the depot. Interesting would be to investigate if they are collected at the same time and by whom, if its formal or informally paid.

6.6. Other Observations



Figures 47a; b - Different views, at different heights. One of the attractive aspects of living in most of the hilly informal settlements of the region. On the background it's possible to see the famous postcards of Rio de Janeiro, the Sugar Load and Christ the Redeemer. These characteristics would deem market value to these houses if it weren't the informality and associated violent issues.

Figure 48 - Community mailbox installed by the state mail company Correios. Located on the bottom of the settlement that receives the mail of all the residents. It is perceived positively by the residents we spoke as it is a form of guaranteed that mail can be delivered, as before that there was no way to refer to house addresses reachable by mail workers.

Figure 49 – The local "quadra" (court), a public space where a bar is located and historically, gatherings used to happen for leisure in the nights and weekends. Due to the risks posed by bad state of conservation of the roof the frequency of costumers is not the same, rendering less useful this common space of interactions between the residents.

Figure 50 – City council works and the sign publicizing the construction, at the cost of 90.000 Reais, of a small space of an elderly open air gym (a few metal structures that serve as the equipment's composes it, and its accompanied by 3 concrete tables with 4 benches). Despite being an intervention made for the public common use, Local residents commented it was never a demand from the community, but the local resident association played its part on "accepting" the investment. It could be tried to reach the stakeholders, in this case the city council to know if there is any sort of technical material that could serve for a quantification of the materials used in this public intervention also.